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Framework for the Assessment of Atlantic Halibut Stocks on Scotian Shelf and Southern Grand Banks

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT iv
RÉSUMÉ v
INTRODUCTION 1
STATISTICAL CATCH-AT-LENGTH MODEL: SCAL 2
OBJECTIVE FUNCTION MINIMIZATION APPROACH 3
SCAL FITS TO ABUNDANCE AND LENGTH COMPOSITION DATA 4
SCAL ESTIMATES OF ABUNDANCE, RECRUITMENT, AND EXPLOITATION 5
FORCASTING METHODOLOGY AND INTERIM MANAGEMENT PROCEDURES 5
MULTI-FLEET AGE-/LENGTH-STRUCTURED OPERATING MODEL: HAL 6
CLOSED-LOOP SIMULATION ALGORITHM FOR EVALUATING HARVEST STRATEGIES 7
PERFORMANCE DIAGNOSTICS 7
HARVEST STRATEGY SIMULATION RESULTS 8
DISCUSSION 8
REFERENCES CITED 10
TABLES 11
FIGURES 25
APPENDICES 48
APPENDIX 1: INDICES OF ABUNDANCE AND LANDINGS 48
APPENDIX 2: RETROPSECTIVE PATTERNS 51
APPENDIX 3: HAL SIMULATIONS WITH BEVERTON HOLT RECRUITMENT 52

ABSTRACT

Atlantic halibut is the most valuable groundfish species per unit weight landed on the Atlantic coast. In recent years it has become one of the most valuable groundfish fisheries in Atlantic Canada. The 2014 framework for Atlantic halibut on the Scotian Shelf and Southern Grand Banks developed new methods for monitoring stock size and productivity, forecasting long-term performance of a range of fishing mortality (F) strategies, and evaluating performance of alternative management strategies. In this document, the authors describe: (i) a comprehensive statistical catch-at-length assessment model (SCAL) to be used in the stock assessment years, (ii) a proposed interim procedure for deriving annual total allowable catch (TAC) advice between stock assessments, and (iii) an operating model (HAL) for evaluating performance of alternative TAC interim procedures (i.e., for testing the proposed interim procedure). A Fisheries and Oceans Canada (DFO) Canadian Science Advisory Secretariat science peer review process provided opportunity for scientific peer review of data inputs, model structure, reference points, interim procedure, harvest strategies and objectives for the fishery. The SCAL model estimates of spawning stock biomass (SSB) between 1970 and 2013 indicate that the halibut stock has increased from the depleted state of the early-1990s to the present. The SSB in 2013 is estimated to be 6,668 mt (Standard Error=234 mt). Legal-sized (greater than 81 cm since 1994) exploitation rate suggests that there were short periods of intense exploitation in the 1970s and early-1990s; current exploitation rates are the lowest on record and are below the natural mortality (M) rate of M=0.14 estimated from a multi-year mark-recapture model. The stock-recruit relationship for halibut could not be well described by the more commonly used models; therefore, interim reference points were chosen. The limit reference point (B_{LIM}) was defined as the minimum SSB in the time series (1982-2013) that produced 50% of the maximum recruitment and the upper stock reference point (B_{UPPER}) was defined as the highest SSB in the time series. The assessment and operating models currently depict similar dynamics of halibut sex-specific growth, mortality, and at-sea discarding of under-sized fish in the four main fisheries. The interim procedure uses an empirical harvest control rule based on a 3-year running average of the DFO-Industry Halibut Survey and the DFO 4VWX Research Vessel survey index of recruitment. Based on HAL model simulation, fixed TAC strategies increased the probability of falling below the reference points by 2045 with the same level of catch. The higher F strategies (i.e., F=0.14, F=0.15 and F=0.2) resulted in higher catches in the short term (2014-2024) before declining in the medium (2025-2035) and long term (2035-2045), whereas with the F=0.1 strategy the short-term increase in catch is smaller, but the projected catch is higher in the medium and longer term. Release of live halibut greater than 125 pounds (167 cm), assuming fecundity is proportional to biomass, did not improve stock performance with either constant F or constant TAC, and in some cases led to increased probability of falling below B_{UPPER}. There was no indication that increasing the minimum legal size to 85 cm would impact stock performance as measured by the probability of falling below reference points or projected catch.

Cadre d'évaluation pour les stocks de flétan de l'Atlantique du plateau néo-écossais et du sud des Grands Bancs

RÉSUMÉ

Le flétan de l'Atlantique est l'espèce de poisson de la côte Atlantique la plus importante par poids unitaire débarqué. Au cours des dernières années, cette pêche de poisson de fond est devenue la plus importante au Canada atlantique. Dans le cadre de 2014 pour le flétan de l'Atlantique du plateau néo-écossais et du sud des Grands Bancs, on a élaboré de nouvelles méthodes de surveillance de la taille et de la productivité des stocks, de prévision du rendement à long terme d'une gamme de stratégies concernant la mortalité par pêche (F) et d'évaluation du rendement des stratégies de rechange en matière de gestion. Dans le présent article, nous décrivons : (i) un modèle d'évaluation statistique détaillé des prises selon la longueur, qui sera utilisé durant les années d'évaluation du stock, (ii) une procédure temporaire proposée pour obtenir un avis sur le total autorisé des captures (TAC) annuelles entre les évaluations du stock et (iii) un modèle opérationnel pour l'évaluation du rendement des autres procédures temporaires sur le TAC (c.-à-d. pour les mises à l'essai de la procédure temporaire proposée). Un processus scientifique d'examen par les pairs du Secrétariat canadien de consultation scientifique de Pêches et Océans Canada a fourni une occasion pour mener une consultation scientifique par des pairs de l'entrée des données, de la structure du modèle, des points de référence ainsi que des stratégies et des objectifs relatifs à la pêche. D'après le modèle statistique des prises selon la longueur, les estimations des niveaux de la biomasse du stock reproducteur entre 1970 et 2013 indiquent que le stock de flétan a augmenté depuis l'épuisement observé au début des années 1990. La biomasse du stock reproducteur (BSR) en 2013 est estimée à 6,668 tm (écart-type = 234 tm) Le taux d'exploitation des flétans de taille réglementaire (plus de 81 cm depuis 1994) laisse supposer qu'il y a eu de courtes périodes d'exploitation intense dans les années 1970 et au début des années 1990; les taux d'exploitation actuels sont les plus faibles jamais enregistrés et se situent en dessous du taux de mortalité naturelle de M=0,14 estimé à partir d'un modèle pluriannuel de marquage-recapture. La relation stock-recrutement pour le flétan ne pouvait pas être correctement décrite par les modèles les plus couramment utilisés; par conséquent, des points de référence provisoires ont été choisis. Le point de référence limite (B_{LIM}) a été défini comme la biomasse du stock reproducteur minimale de la série chronologique (de 1982 à 2013) qui a produit 50 % du recrutement maximal, tandis que le point de référence supérieur (B_{UPPER}) a été défini comme la plus haute biomasse du stock reproducteur de la série chronologique. Les modèles d'évaluation et d'exploitation indiquent à l'heure actuelle des dynamiques semblables pour la croissance propre au sexe du flétan, la mortalité et le rejet en mer des poissons de taille non réglementaire des quatre pêches principales. La procédure temporaire utilise une règle empirique de contrôle des prises, fondée sur une moyenne mobile de trois ans du relevé sur le flétan mené par l'industrie et le MPO et du relevé sur l'indice de recrutement réalisé par le navire de recherche du MPO dans la division 4VWX. Selon une simulation du modèle HAL, des stratégies pour un total autorisé des captures (TAC) fixe augmentaient la probabilité de passer sous les points de référence d'ici 2045 avec le même niveau de prises. Des stratégies de mortalité par pêche (F) plus élevées (F=0,14, F=0,15 et F=0,2) entraînent des prises plus élevées à court terme (de 2014 à 2024) avant de diminuer à moyen (de 2025 à 2035) et à long (de 2035 à 2045) termes. Avec la stratégie F=0,1, l'augmentation à court terme des prises est plus faible, mais les prises prévues sont plus élevées à moyen et à long termes. Les remises à l'eau de flétans vivants de plus de 125 livres (167 cm), si l'on suppose que la fécondité est proportionnelle à la biomasse, n'ont pas permis d'améliorer le rendement du stock avec une mortalité par pêche constante ou un total autorisé des captures constant et, dans certains cas, ont entraîné une probabilité accrue de passer sous le point de référence supérieur. De plus, rien n'indique qu'une augmentation de la taille réglementaire minimale à 85 cm aurait des effets sur le rendement du stock, mesuré par la probabilité qu'il passe sous les points de référence ou des prises prévues.

INTRODUCTION

Atlantic halibut is the most valuable groundfish species by landed weight on the Atlantic coast and, in recent years, has also come to be one of the highest in overall landed value. Until 1988, the halibut fishery in Canadian waters was unregulated. Two management units, Northwest Atlantic Fisheries Organization (NAFO) Divisions 4RST and 3NOPs4VWX5Zc, were defined based primarily on tagging studies (McCracken 1958, Bowering 1986, Stobo et al. 1988) and differences in growth rates (Neilson and Bowering 1989). A total allowable catch (TAC) of 3,200 mt for 3NOPs4VWX5Zc halibut was first established in 1988 and was reduced to a low of 850 mt in 1995, in response to an 8 year decline in landings. Since 1988, management plans and licence conditions require the release of halibut less than 81 cm in length. Beginning in 1999, the TAC has been increased several times and was set at 2,563 mt in 2014, which is well below peak landings in the early-1960s and mid-1980s, and above average landings from 1960 to 2013 of approximately 1,800 mt.

Prior to 2010, assessment advice was provided based on the Fisheries and Oceans Canada (DFO) 4VWX Research Vessel (RV) groundfish trawl survey abundance indices, catch per unit effort and length composition of catch (e.g., Perley et al. 1985, Zwanenberg et al. 2003). The last assessment of Atlantic halibut was conducted in November 2010 (DFO 2011). This assessment used a length-based age-structured assessment model and produced estimates of spawning stock biomass (SSB) and fishing mortality (F). The consequences of different harvest levels and the risk to the productivity of the stock were assessed in 2012 (DFO 2012). Based on model projections, using two different spawner-recruit curves, 3NOPs4VWX5Zc Atlantic halibut spawning stock biomass was expected to increase and the population was concluded to be in a productive period due to high recruitment. It was also concluded that there was little risk in harming the productivity of the stock over 3 years at harvest levels below 4,000 mt. A stock status update in November 2013 (DFO 2014) concluded, based on indices of abundance (4VWX RV survey, DFO-Industry Halibut Survey) and estimates of fishing and natural mortality from tagging, that the 3NOPs4VWX5Zc Atlantic halibut stock was increasing despite moderate increases in TAC.

The 2014 assessment framework for Atlantic halibut on the Scotian Shelf and Southern Grand Banks, presented herein, developed new methods for monitoring stock size and productivity, forecasting long-term performance of a range of F strategies, and evaluating performance of alternative management strategies (DFO 2015). Rather than identify a set of competing methods, we present a complementary package of models that work together to provide robust advice about fishery benefits and risks. In this paper, the following is described:

(i) a comprehensive statistical catch-at-length assessment model (SCAL) stock assessment model to be used in the stock assessment years,
(ii) a proposed interim procedure for deriving annual TAC advice between stock assessments, and
(iii) an operating model (HAL) for evaluating performance of alternative TAC interim procedures (i.e., for testing the proposed interim procedure.

The framework uses a statistical catch-at-length (SCAL) model that estimates historical biomass, fishing mortality, recruitment and biological reference points, and is used to condition, or parameterize, the operating model. The interim procedure uses an empirical harvest control rule based on a 3-year running average of the halibut longline survey. The framework model (SCAL) and the halibut operating model (HAL) currently depict similar dynamics of halibut sex-specific growth, mortality, and at-sea discarding of under-sized fish in the four main fisheries. A DFO Canadian Science Advisory Secretariat (CSAS) external peer review process (DFO 2015)

provided opportunity for review of data inputs, model structure, reference points, interim procedure, harvest strategies and objectives for the fishery. Additionally, this framework provided a unique interactive opportunity for provision of science advice on the suite of strategies, performance indicators, and associated risks of different fishery harvest strategies.

STATISTICAL CATCH-AT-LENGTH MODEL: SCAL

In this section, we develop a statistical catch-at-length (SCAL) model for estimating historical biomass, fishing mortality, and recruitment of Atlantic halibut on Scotian Shelf and southern Grand Banks, as well as biological reference points. The data inputs are essentially the same as with the earlier assessment model (Trzcinski et al. 2011, den Heyer et al. 2015; Appendix 1), although the treatment of the length composition data varies. The SCAL model combines an age-structured model of population dynamics with a likelihood functions based on catch-at-length data. Age composition is mapped to length composition by first computing the distribution of lengths at a given age and then summing those distributions over ages to get the marginal distribution of lengths alone. The assumed relationships between age and length for both male and female halibut are given in Table 1 along with other model notation. We develop the model sequentially from equilibrium unfished characteristics to predicted values for biomass indices, length composition, and proportion female-at-length data. Although we derive the unfished characteristics, we assume the halibut stock was in a non-equilibrium condition in 1970 since there was considerable fishing activity over the preceding 100 years.

The equilibrium characteristics are computed sequentially in Table 2 based on the growth, maturity, and fishery selectivity schedules (computed in Table 3) and a parameter vector ("big omega") $\Omega = \left(\tilde{\mathbf{F}}, \Theta\right)$ consisting of a fishing mortality rate vector $\tilde{\mathbf{F}}$ and dynamic model parameters ("big theta") $\Theta = \left(\Theta^{est}, \Theta^{fixed}\right)$. Setting $\tilde{\mathbf{F}} = 0$ gives the equilibrium unfished conditions for female spawning stock biomass-per-recruit (equation SL.5), recruitment (SL.6), and female spawning biomass (SL.7) needed to compute biological reference points. Maximizing the landed catch in SL.8 with respect to the input $\tilde{\mathbf{F}}$ obtains an estimate of the maximum sustainable yield.

The SCAL dynamic model in Table 3 partitions the model parameters into four subsets consisting of leading parameters (Θ^{est}), nuisance catchability and variance parameters estimated conditionally on the leading parameters (Θ^{cond}), fixed parameters for growth, maturity, discard mortality rates, and selectivity parameters that are not estimated (Θ^{fixed}), and parameters specifying the prior distributions (Θ^{priors}) for some of the leading parameters. The *estimated* and *fixed* parameter subsets are given in the main SCAL model Table 3, although membership in these objects may vary depending on the final estimability of certain parameters.

Initial conditions in 1970 assume that the stock was in a non-equilibrium state with respect to long-term average recruitment. Equation SL.16 specifies the initial abundances as a function of log-normally distributed recruitments and a historical average fishing mortality rate vector $\mathbf{F}_{init}$, which is among the leading parameters estimated in the model. The elements of $\mathbf{F}_{init}$ are the long-term average fishing mortality rates for each of the four fisheries in the model: Longline NAFO Divisions 3NOPs (LL.3), Otter trawl NAFO Divisions 3NOPs (OT.3), Longline NAFO Divisions 4VWX5Zc (LL.4), and Otter trawl NAFO Divisions 4VWX5Zc (OT.4). This parameterization of the initial abundances-at-age treats pre-1970 recruitments under the same assumptions as post-1970 recruitments, which helps to stabilize the overall estimation procedure compared to modeling the initial abundances-at-age separately as leading

parameters. The latter approach may be applicable for age-composition data, but probably not for length data due to smearing of age information across the length distribution.

The SCAL model tracks the dynamics of male and female halibut separately (SL.17-18) because differences in size-at-age result in age-specific differences in selectivity. These differences are captured in the gender-specific total mortality rates $Z_{t,g,x}$, which are obtained by first solving the catch equation in SL.21 (via a Newton-Raphson procedure) for the annual fully-selected fishing mortality rates $F_{t,g}$ and then substituting those into the total mortality equation in SL.22 We note two features of the catch equation. First, it simply adds fully-selected male and female biomass-at-age, which means that the proportion female is a predicted quantity rather than a data input. There is a likelihood component for proportion female in the catch; however, the model does not currently fit to this data since it is somewhat redundant information to the male, female, and sexes combined age composition. Nevertheless, the model actually fits the data reasonably well in most circumstances. Second, the modeled catch represents the landings since only the proportions $P_{g,t,a,x}$ are retained and landed. Total mortality accounts for both landed fishing mortality and discard mortality via the proportion released-at-age (1- $P_{g,t,a,x}$) and the fishery-specific discard mortality parameters d_g.

The SCAL model is fitted to:

(1) a relative abundance index from the DFO 4VWX RV survey (RV_4VWX; 1970-2013),
(2) 3NOPs4VWX DFO-Industry Halibut Survey biomass CPUE (HS, 1998-2013), and
(3) male, female, and combined proportion-at-length data for longline commercial fisheries (1988-2013), RV_4VWX (1970-2013), and HS (1998-2013) surveys.

Predicted values for the RV_4VWX (g=5) and HS (g=6) surveys are given separately because the former indexes numbers of fish, while the latter indexes available biomass. The proportions-at-length for males and females are also based on fully-selected numbers-at-age. Proportions-at-length for the at-sea observer samples (SL.25, sexes combined noted by "c") do not account for the proportion retained-at-age that occurs in the sexed samples.

Model parameters are estimated using a Bayesian approach given in Table 4. The sequence of equations in SL.26-39 leads from log-normally distributed abundance (or catch per unit effort, CPUE) residuals $z_{g,t}$ and multivariate-logistic distributed length-proportion residuals $\eta_{g,l,t,x}$ to concentrated data log-likelihoods (SL.34-35), prior distributions on stock-recruitment (SL.37) and natural mortality parameters (SL.38), and the total negative log-posterior distribution (SL.39). The carat symbol "^" indicates an estimate that is conditional on the leading parameters (i.e., these are parameters in Θ^{cond} mentioned above). The sample sizes for abundance indices $\mathbf{n}_{g,t}$ and length proportions $\mathbf{n}_{g,t,x}$ used in the variance and concentrated likelihood estimates are accumulated for non-missing data only.

OBJECTIVE FUNCTION MINIMIZATION APPROACH

The overall negative log-posterior function is minimized in several phases (currently up to 6 phases are used) within AD Model Builder (Fournier et al. 2012). Biomass scaling parameters $\bar{R}$ and F_{init} are estimated first, followed by the recruitment process errors, selectivity, and natural mortality. During the early phases, it helps to treat the 4VWX RV survey as an absolute abundance estimate (by setting idxRelative(1)=0) so that 4VWX RV survey catchability is set equal to 1 rather than a relative index, which is the default setting in the ADMB input data file. Absolute abundance helps to provide scale to the model and improves stability during early estimation phases while fitting the length-composition. In the last phase, the index can be reset

to relative (by setting idxRelative(1)=1), which then allows for estimation of catchability. Using this approach, the estimate of 4VWX RV survey catchability is about 0.68 (after adjusting for 4VWX RV survey selectivity), which is comparable to other 4VWX RV survey catchability estimates in other SCAL models (e.g., Southern Gulf of St. Lawrence Cod). The fitting procedure can be further improved by setting the index time-series weights $\lambda_{g,I} \sim 10$ (Equation SL.9) in the last phase, which forces the model to fit the index data well. If this is not done, then the model will continue to put greater emphasis on all the length composition data, which typically results in poor fits to long-term survey trends.

For Bayesian assessments of model uncertainty, SCAL outputs the estimated model parameters Θ^{est} as well as derived quantities and time-series, including unfished spawning biomass and recruitment, annual spawning biomass, age-1 recruitment, fully-selected fishing mortality, legal biomass, selectivity function parameters, and natural mortality. Bayes posterior distributions for these quantities are obtained via Markov Chain Monte Carlo (MCMC) sampling. MCMC chains of 500,000 iterations with a thinning interval of 250 produce 2500 samples, of which the first 500 may be dropped for burn-in. This results in a posterior sample of 2000 values that can be used to summarize posterior distributions as well as for biological reference point computations.

SCAL FITS TO ABUNDANCE AND LENGTH COMPOSITION DATA

The SCAL model captures the main features of the 4VWX RV survey abundance and DFO-Industry halibut longline survey biomass (Figure 1). Survey standard errors estimated from these fits were 0.26 and 0.195, respectively, which are quite reasonable for fishery-independent survey data. There was no indication of a retrospective pattern for model estimates of spawning stock biomass (Appendix 2).

Two periods of increased catch occur in the 4VWX RV survey between 1970 and 1980 and between 1984 and 1994. Although both results from periods of above-average recruitment, the second increase did not materialize into exploitable or spawning stock biomass because they were heavily fished and discarded during the late-1980s. The early increase did materialize into exploitable fish as indicated by the bulge in the halibut biomass in the 1980s (Figure 1, lower panel). The differences in timing reflect later age-at-50% selectivity for the DFO-Industry halibut survey (around 5 years) compared to the 4VWX RV survey (about 1.5 years, Figure 2). In addition, the increase of recruitment passes through the 4VWX RV survey over a few years because of declining selectivity-at-age as halibut get older and larger. This dome-shaped selectivity pattern is similar to other trawl gear on Pacific halibut. Selectivity in SCAL is length-based, so the estimated patterns could be compared to selectivity estimates derived from halibut tagging data.

Information about length-based selectivity is mainly obtained via SCAL model fits to length composition data (Figures 3-5). Like the abundance surveys, the fits to these data are reasonably good judging by the estimated standard errors (Table 5), which range from 0.285 (halibut survey females) to 0.812 (OT.3 males). Fits to the combined sexes samples are better for all datasets, which is to be expected. There is some indication of lack-of-fit on the descending limb of some length compositions, suggesting that perhaps mortality, growth, or selectivity parameters could be better specified. Preliminary trials estimating M indicated higher rates for males (approximately 0.2).

SCAL ESTIMATES OF ABUNDANCE, RECRUITMENT, AND EXPLOITATION

The SCAL model predictions of spawning stock biomass for 1970-2013 suggest that the halibut stock is growing from a heavily depleted state in the early-1990s (Figure 6). The 81 cm size limit regulation enacted in 1994 caused a considerable reduction in legal-sized halibut biomass. Estimated spawning stock biomass in 2013 of 6,668 tonnes is approximately 8% of the equilibrium-unfished level of 79,809 tonnes. Total and legal halibut biomasses have been growing faster than the spawning stock because these state variables include either all ages (total biomass) or younger ages than currently appear in the female spawning stock (female maturity assumed 8.5 years at 50% and 11.5 years at 95%).

Estimates of age-1 halibut abundance indicate two periods of high recruitment, one in the early 1970s and another recently from 2005-2010 (Figure 7). Recruitment shows alternating periods of above and below average recruitment with better periods in the mid-1970s, late-1980s, and 2006-2010. The relationship between halibut spawning biomass and recruitment shows no consistent pattern over the entire history (Figure 8) with high and low recruitment occurring at both high and low spawning stock biomass levels (Figure 9). Note, however, that spawning stock biomass estimates before the mid-1980s are probably not that reliable because the 4VWX RV survey is the only abundance index available for that time period and it mainly tracks recruitment (which could explain why recruitment estimates during the 1970s are fairly precise in Figure 7).

SCAL model estimates of the legal-sized exploitation rate (Figure 9) suggest that current exploitation rates are the lowest on record. There were two short periods of intense exploitation in the 1970s and early-1990s following the period of peak catches and stock decline. Estimated fishing mortality rates were generally higher than those derived from mark-recapture over the past few years (den Heyer et al. 2015), although the temporal trends are similar. The relationship between these historical fishing mortality rates and spawning stock biomass suggest that fishing intensity increased during period of low abundance (Figure 10), while fishing mortality over the past several years has been relatively stable and below the female halibut natural mortality rate assumed in the model.

FORCASTING METHODOLOGY AND INTERIM MANAGEMENT PROCEDURES

This section describes an operating model (i.e., described as forecasting methodology in terms of reference) for evaluating alternative interim management procedures for setting annual halibut TACs that meet conservation and economic objectives. The halibut operating model is meant to provide a practical, yet realistic representation of halibut stock dynamics, fishery harvesting process, and monitoring data so that non-linear stock dynamics, time lags, and data uncertainties can be taken into account in annual TAC advice. These processes, along with regulations such as legal size limits and at-sea release protocols, interact to determine short- and long-term performance of fishery harvest strategies. Simulating candidate management procedures against a suite of operating models provides a robust approach to assessing fishery compliance with both national and international fishery policies.

A multi-fleet, sex-/age-structured operating model (HAL) was used to evaluate a suite of constant TAC and constant F harvest strategies defined at the November 3-6, 2014 framework meeting Terms of Reference (DFO 2015). It was decided at the framework meeting that a 3-year mean of the halibut survey abundance index would be the basis of interim advice between stock assessments. HAL was parameterized based on the SCAL framework stock assessment model to represent an age-structured Atlantic halibut stock further structured by male/female growth and mortality rates, four fisheries (LL.3 - longline NAFO Divisions 3NOPs, LL.4 - longline NAFO Divisions 4VWX5Zc, OT.3 - otter trawl NAFO Divisions 3NOPs, and OT.4 - otter trawl

NAFO Divisions 4VWX5Zc), biological sampling programs (RV_4VWX and HS surveys), and a suite of interim harvest control rules based on HS indices of halibut exploitable biomass. The constant F harvest control rule simulated in each future year (t) is defined by the following five-step procedure that includes the Scotia Fundy Groundfish Advisory Committee limit of change in TAC by 15% up or down in a given year:

Step 1: Choose a target fishing mortality rate, F (e.g., F=0.15)

Step 2: Compute the 3-year average of the Halibut Survey index, call it HS(t)

Step 3: Compute the estimated survey biomass via,

B(t)=HS(t)/0.00479, where 0.00479 is HS catchability estimate from SCAL

Step 4: Compute the proposed TAC for year t, call it TAC*(t)

TAC*(t)=(1-exp(-F)) x B(t)

Step 5: Implement 15% change limit by choosing the appropriate case:

Case 1: TAC*(t) > 1.15 x TAC(t-1) or TAC* is more than 15% greater than last year

set TAC(t)=1.15 x TAC(t-1)

Case 2: TAC*(t) < .85 x TAC(t-1) or TAC* is more than 15% less than last year

set TAC(t)=0.85 x TAC(t-1)

Case else: TAC* is within +/- 15% of last year

set TAC(t)=TAC*(t)

The TAC(t) for each year is then allocated among fisheries in the following proportions: LL.3=0.2185, OT.3=0.01263, LL.4=0.72715, OT.4=0.0408, which were the landed catch proportions observed in 2013.

HAL simulations (see Table 6) were used to quantify the relative risks and benefits of applying constant TACs (2,400, 2,600, 2,800 mt) and constant fishing mortality rates (F=0.1, 0.125, 0.14, 0.15, 0.20) with annual changes in the TAC limited to 15% or less (the five-step procedure given above). These harvest strategies were also tested with and without increasing the minimum legal size from 81 cm to 85 cm and voluntary release of halibut greater than 125 pounds (167 cm; assuming 100% post-release survival). Natural mortality (M=0.15) and discard mortality rates in longline and trawl fisheries were the same as those used in the SCAL model.

MULTI-FLEET AGE-/LENGTH-STRUCTURED OPERATING MODEL: HAL

Mathematical notation for HAL is given in Table 7 and equations specifying HAL dynamics and computational algorithm are given in Table 8. HAL represents a halibut population that is structured by age and sex, where the latter dimension is used to represent variation in halibut size-at-age that occurs via sexually dimorphic growth. Equations describing unfished equilibrium quantities and theoretical biological reference points are identical to those derived for SCAL (Table 2).

Halibut mean length (cm) for age-*a* and sex-*x* is modeled using a von Bertalanffy growth function (OM.1). Size-based discarding at-sea is modelled in two parts: (i) fish are first brought onboard fishing vessels according to gear-specific selectivity functions that depend on halibut length (OM.4) and then (ii) fish smaller than the legal size limit are all released according to a descending logistic function of length (OM.5). Discarding relationships in OM.5 are not available, so we assumed a knife-edged function at the size limit.

The current HAL operating model begins with the age-/sex-composition estimated by SCAL for 1998 (OM.7). Recruitment of age-1 individuals in each sex-class occurs on January 1st of the model year and is computed by combining long-term average recruitment with annual deviations from the average (OM.8-9). Parameters representing the unfished spawning stock biomass (B_0) and average recruitment are input from SCAL along with annual recruitment deviations for the historical period 1998-2013. Note that these recruitments are denoted in the SCAL model notation.

For both the historical and forecasting periods, we solve the catch equation (OM.12) for Ft,g given the landed catch by gear for the historical period or total landed quota for future projections (i.e., assuming all the quota is taken every year). Predicted values for at-sea discards (OM.13) are computed based on the resulting $F_{t,g}$ values in same way during historical and projection periods. Quotas during the forecasting period are derived using the constant F algorithm defined above or are set to constants for the entire forecasting period for the constant TAC options.

CLOSED-LOOP SIMULATION ALGORITHM FOR EVALUATING HARVEST STRATEGIES

The following algorithm was used to simulate performance of alternative management procedures over two generations (28 years):

1. Define an inter-framework management procedure based on (i) 3-year running average of DFO-Industry Halibut Survey, (ii) harvest control rule (constant F or constant TAC), (iii) size limit regulation, and (iv) voluntary release option;
2. Initialize HAL for the period 1998-2013 based on SCAL output;
3. Project the operating model population and fishery one time step into the future and apply the following:
    a. Generate and append new survey biomass indices (1.i) and landed catch to the existing HS observation dataset;
    b. Apply the harvest decision rule defined above to generate a quota;
    c. Update the operating model population given the total mortality rate (i.e., fishing + discard + natural mortality) generated by the final landed catch limit, catch allocation among fisheries, size limit regulation (1.iv), voluntary release (1.v), and new recruitment; and
    d. Repeat Steps 3a-3c until the projection period ends.
4. Calculate quantitative performance statistics for the simulation replicate; and
5. Repeat Steps 2-4 for 100 replicates, each of which applies a new sequence of random recruitment process and survey index observation errors.

PERFORMANCE DIAGNOSTICS

Assessing performance of management procedures simulated using the above algorithm was done quantitatively based on a suite of conservation and catch performance requirements. For the Atlantic halibut assessment, conservation performance is measured with respect to Critical, Cautious, and Healthy zones defined by provisional reference points limit reference point (B_{LIM}) equals 2,600 mt (Critical-Cautious boundary) and upper stock reference point (B_{UPPER}) equals 6,668 mt (Cautious-Healthy boundary). The B_{LIM} was defined as the minimum SSB in the time series (1982-2013) that produced 50% of the maximum recruitment and the B_{UPPER} was defined

as the highest SSB in the time series. Catch performance of candidate management procedures was measured using the median average fishery catch over 10-year forecasting intervals representing short (2014-2025), medium (2026-2035), and long (2036-2045) term. Performance measure computations (P.1-P.3) are given in Table 9.

HARVEST STRATEGY SIMULATION RESULTS

Harvest strategies involving higher minimum size of landed halibut (85 cm) and/or voluntary release of large halibut (>167 cm) resulted in lower catch and poorer conservation performance than those with status quo size limit (min. 81 cm). For the constant 2,400 mt TAC strategy and 81 cm minimum size limit and voluntary releases of large halibut, simulated spawning biomass trajectories remained well above B_{UPPER} for most of the 28-year projection period. Maintaining such high biomass also resulted in a negligible probability of the simulated biomass dropping below B_{LIM}. The same constant 2,400 mt TAC combined with a higher size limit or voluntary release of large halibut resulted in lower spawning biomass over the last 10 years and also non-zero probabilities of biomass dropping below B_{LIM} in the long-term (Figure 11). Voluntary release of large halibut had more of a negative effect on long-term biomass than the larger size limit across all TAC and F harvest strategies we investigated.

The constant F strategies generally obtained greater overall catch than the TAC strategies, but the biggest differences were in the short-term projection period. Higher short-term catch led to lower peak biomasses and faster medium-term declines from the peak, but also more stable long-term biomass. The F=0.10 strategy maintained spawning biomass above B_{LIM} in 99% of the simulations and B_{UPPER} in 88% (Table 10) unless a voluntary release option was used (Figure 12). Increasing the target fishing mortality rate to F = 0.125 led to slightly higher-shorter term catch, and spawning biomasses above B_{LIM} in 98% of the simulations and B_{UPPER} in 44% (Figure 13, Table 10). This F strategy had the highest catch for those strategies in which the probability of $B < B_{LIM}$ was less than 5%. Although higher $F > 0.125$ strategies gave higher average catch, the probabilities of $B < B_{LIM}$ went from 13%, 23%, and 47%, respectively for F = 0.14, 0.15 (Figure 14), and 0.20 (Table 10). For these F strategies, very high short-term catch ultimately led to lower medium- and long-term catch because the stock was maintained at low levels (Figure 15).

DISCUSSION

The Scotian Shelf and southern Grand Banks Atlantic halibut stock has a history of overfishing that pre-dates the time series used in the stock assessment model (i.e., prior to 1970). The new statistical catch-at-length assessment model (SCAL) estimates historical biomass, fishing mortality, recruitment, and is used to condition the operating model (HAL). The 2013 spawning stock biomass is estimated to be 6,668 mt (SE=234 mt), the highest in the time series, and the legal-sized (greater than 81 cm since 1994) biomass (B=23,479 mt, SE=664 mt) is also well above all other estimates. Current exploitation rates are the lowest on record and are below the natural mortality rate (M=0.14) estimated from a multi-year mark-recapture model (den Heyer et al. 2015) and used in the SCAL model. This stock has increased from the depleted state observed in the 1990s, but the potential for growth remains unknown.

The stock-recruit relationship for halibut was not well described by typical stock-recruitment models; therefore, provisional biological reference points were chosen. A better understanding of the stock recruitment relationship would be necessary to develop biological reference points based on maximum sustainable yield (e.g., B_{MSY}). In the meantime, consideration could be given to alternative biological reference point proxies derived from spawning stock-per-recruit or yield-per-recruit concepts.

Uncertainty in abundance indices, catch length composition, and biological data (for review see: den Heyer et al. 2015) may lead to biased estimates from the SCAL assessment model. The growth models used in this assessment are biased by size-selectivity of the fishing gears (Armsworthy and Campana 2010) used to collect length-at-age samples. Further, the length-stratified selection of otoliths for the growth models may also bias estimates of growth and its variability. Finally, as there has been no aging of otoliths since 2007, it is not possible to assess whether recent increases in halibut abundance have resulted in density-dependent declines in growth rate.

The implications of uncertainty about the biology of Atlantic halibut could be explored, either by using different assumptions of natural mortality or different stock-recruit relationships in the harvest strategy simulations. For instance, an alternate Beverton-Holt formulation of the stock-recruitment relationship in the projection model, which was originally presented at the assessment meeting (Appendix 3), demonstrates how biological uncertainty changes the projection outcomes for population growth and fishery yield. The Beverton-Holt stock-recruitment formulation led to higher short-term yield for all F-based strategies and higher probabilities of spawning biomass below B_{LIM} for both F-based and TAC-based stragies; however, the F = 0.125 strategy still resulted in $p < 0.05$ of biomass dropping below B_{LIM}. Future assessment model development would also benefit from data or simulations to explore the form of size-selectivity by the longline fishery. As larger halibut are primarily mature females, reproductive behaviours and/or changes in distribution may affect fishery and/or survey catchability. Also, given the reduced commercial value of large halibut, there may be modifications in fishing practices aimed at reducing catch of large halibut. Mis-specification of the selectivity curve as flat instead of dome-shaped could lead to underestimation of the population size in some or all years.

The Scotian Shelf and southern Grand Banks Atlantic halibut stock is on a 5-year assessment cycle. An interim assessment procedure based on the q-adjusted 3-year mean of the DFO-Industry halibut survey index of exploitable biomass was evaluated in simulations using the HAL operating model. The HAL model assumes no changes in vital rates such as survival, growth, or fecundity, and assumes that the recruitment will return to the long-term mean. The provisional reference points provide benchmarks to assess risk over short, medium and long term. In general, fixed TAC strategies increased the probability of falling below the reference points by 2045 with the same level of catch as constant F strategies. The higher F strategies (F=0.14, F=0.15 and F=0.2) resulted in higher catches in the short term (2014-2024) before declining in the medium (2025-2035) and long term (2035-2045), whereas with the F=0.1 strategy, the short-term increase in catch is smaller, but the projected catch is higher in the medium and longer term. Release of live halibut greater than 125 pounds (167 cm), assuming fecundity is proportional to biomass, did not improve stock or fishery performance with either constant F or constant TAC, and in some cases led to increased probability of falling below B_{UPPER}, because of higher fishing intensity on smaller fish. There was also no indication that increasing the minimum legal size to 85 cm would impact stock performance as measured by the probability of falling below reference points or projected catch. All F strategies evaluated included a cap on the change of TAC (up or down) of 15% or less. This constraint on TAC change delays the peak in landings relative to the peak in biomass. The offset is greatest for lower F strategies.

The 2014 framework accepted for assessing Atlantic halibut on the Scotian Shelf and Southern Grand Banks developed new methods for monitoring stock size and productivity, forecasting long-term performance of alternative management strategies. The stock assessment meeting provided a forum to establish management objectives, interim procedures and define a suite of harvest control strategies for evaluation. Simulating candidate management procedures with the

operating model provided projections to be used to evaluate various strategies against the short, medium and long-term objectives of the fishery.

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TABLES

Table 1. Notation for the statistical catch-at-length model (SCAL). Note cells with dashes indicate empty cells.

Symbol	Value	Description
T	44	Total number of years between 1970 and 2013
A	30	Plus group age-class
t	1,2,...,T	Time step. Corresponding year range is 1970-2013
a	1,2,...,A	Age-class index
l	11,16,...,276	Length class index with 5- cm bin size
g	1,2,...G	Fishery/gear index: 1=LL.3, 2=OT.3, 3=LL.4, 4=OT.4, 5=RV, 6=HS
B_0	-	Unfished female spawning biomass (tonnes)
h	0.95	Stock-recruitment function steepness
q_g	-	Catchability coefficient for gear g
σ_R	0.25	Standard error of log-recruitment
M_x	0.145, 0.145	Natural mortality rates (/yr) for males (x=m) and females (x=f)
$L_{\infty,x}$	134, 205	Asymptotic length (cm) for males (x=m) and females (x=f)
σ_{L_∞}	0.15, 0.15	Coefficient of variation in length-at-age
t_{0x}	0.88,0.49	Apparent age at zero length (yr)
k_x	0.18,0.12	von Bertalanffy growth constant for males and females
c_1, c_2	0.00673, 3.12	length-weight coefficients (i.e., a,b)
$\tilde{A}_{50}$, $\tilde{A}_{95}$	8.5, 11.5	Age-at-50% and -95% maturity
$L_{\lim,t}$	81	Minimum size limit (cm) in year t (beginning 1988)
$\tilde{L}_{50,g,t,a}$, $\tilde{L}_{95,g,t,a}$	-	Ascending limb length-at-50% and -95% selectivity
$\tilde{L}_{50,g,t,d}$, $\tilde{L}_{95,g,t,d}$	-	Descending limb length-at-50% and -95% selectivity
d_g	0.26, 1.26	Discard mortality rate (/yr) for LL.x (g=1,3) and OT.x (g=2,4)
$L_{a,x}$	-	Length-at-age (cm) for males (x=m) and females (x=f)
$w_{a,x}$	-	Weight-at-age for males (x=m) and females (x=f)
m_a	-	Proportion of females mature-at-age
$p_{a,l,x}$	-	Proportion of age class a male (x=m) or female (x=f) halibut in length class l

Symbol	Value	Description
$P_{g,t,a,x}$	-	Proportion of age-*a* males (*x*=*m*) and females (*x*=*f*) retained by fishery *g* in year *t*
$S_{g,t,a,x}$	-	Selectivity for age-*a*, males (*x*=*m*) and females (*x*=*f*) in year *t* by gear-*g*
R_0	-	Unfished equilibrium recruitment
$\phi_{\tilde{\mathbf{F}}}^{SSB}$	-	Spawning biomass per recruit given vector $\tilde{\mathbf{F}}$
ϕ_g^L	-	Landed yield per recruit for gear-*g*
$N_{t,a,x}$	-	Number of age *a* males (*x*=*m*) and females (*x*=*f*) in year *t*
ω_t	-	Log-normal recruitment process deviation
SSB_t	-	Female spawning biomass in year *t*
$C_{t,g,a,x}$	-	Predicted catch-at-age in fishery *g* of males (*x*=*m*) and females (*x*=*f*)
$F_{t,g}$	-	Fully-selected fishing mortality rate for gear *g* in year *t*
$Z_{t,a,x}$	-	Total mortality rate in year *t* for age-*a* males (*x*=*m*) and females (*x*=*f*)
$I_{g,t}$	-	Observed biomass index for gear *g*
$\hat{I}_{g,t}$	-	Predicted biomass index for gear *g*
$\hat{u}_{g,t,l,x=c}$	-	Proportion of length class *l* fish in the landed catch for male (*x*=*m*) and female (*x*=*f*) halibut
$\hat{u}_{g,t,l,c}$	-	Proportion of length class *l* fish in the sexes combined catch sampled at-sea by observers

Table 2. Equilibrium functions of a fishing mortality rate vector $\tilde{\mathbf{F}} = \left(\tilde{F}_1, \tilde{F}_2, ..., \tilde{F}_G\right)$.

Equation	Formula	Description
SL.1	$\Omega = \left(\tilde{\mathbf{F}}, \Theta\right)$	Fishing mortality rates and model parameters
SL.2	$Z_{a,x} = M_x + \sum_{g=1}^{G} S_{g,a,x} \tilde{F}_g \left(P_{g,a,x} + \left(1 - P_{g,a,x}\right) d_g\right)$	Total mortality-at-age/growth group
SL.3	$\ell_{a,x} = \begin{cases} 1 & a = 1 \\ \ell_{a,x} e^{-\hat{Z}_{a-1,x}} & 2 \le a < A \\ \ell_{a-1,x} e^{-\hat{Z}_{a-1,x}} \Big/ \left(1 - e^{-\hat{Z}_{a-1,x}}\right) & a = A \end{cases}$	Survivorship to age *a*
SL.4	$\phi_g^{\mathrm{L}} = \sum_{x=m,f} \sum_{a=1}^{A} \ell_{a,x} w_{a,x} S_{g,a,x} \tilde{F}_g P_{g,a,x} \left(1 - e^{-Z_{a,x}}\right) \Big/ Z_{a,x}$	Landed yield per recruit for gear *g*
SL.5	$\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}} = \sum_{a=1}^{A} \ell_{a,f} m_a w_{a,f}$	Spawning stock biomass per recruit
SL.6	$R = \begin{cases} \bar{R} \\ \left(4hR_0 \phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}} - B_0\left(1-h\right)\right) \Big/ \left(\left(5h-1\right)\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}}\right) \end{cases}$	Total age-1 recruitment for the "avgR" model (top) and Beverton-Holt model (bottom)
SL.7	$B = 0.5 R \phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}}$	Spawning stock biomass
SL.8	$C_g^{\mathrm{L}} = R \sum_{g=1}^{G} \phi_g^{\mathrm{L}}$	Total landed yield for gear *g*

Table 3. Statistical catch-at-length (SCAL) model equations defining the population dynamics and observations for Atlantic halibut. Parameter subsets in SL.1 are as follows: Θ^{est} estimated as free parameters, Θ^{cond} estimated conditional on free parameters, Θ^{fixed} fixed input parameters not estimated, and Θ^{priors} Bayes prior distribution parameters. The subscript "x" is used where parameters have specific male and female values. The subscript "c" denotes a combined male-female sample.

Equations

Parameters

$$\Theta^{est} = \left(\bar{R}, h, B_0, \left\{\delta_a\right\}_{a=1:A}, \left\{\omega_t\right\}_{t=2:T}, M_m, M_f, \left\{\tilde{L}_{50,g,f}\right\}_{g=1:6}^{t=1:n_{S,g}}, \left\{\tilde{L}_{95,g,f}\right\}_{g=1:6}^{t=1:n_{S,g}}, F_{init} \right)$$

$$\Theta^{cond} = \left(\left\{q_g\right\}_{g=5,6}, \left\{\tau^2_{g,f}\right\}_{g=5,6}, \left\{\tau^2_{g,f,x}\right\}_{g=1:6}^{x=m,f,c}, \left\{\tau^2_{g,f}\right\}_{g=1:6} \right)$$

SL.9

$$\Theta^{fixed} = \left(L_{\infty,f}, L_{\infty,m}, k_f, k_m, \sigma_{L,f}, \sigma_{L,m}, \tilde{A}_{50}, \tilde{A}_{95}, \left\{d_g\right\}_{g=1:6} \right)$$

$$\Theta^{priors} = \left(\mu^m_M, \mu^f_M, \sigma^m_M, \sigma^f_M, \mu_h, \sigma_h, \sigma_R \right)$$

$$\Lambda = \left(\left\{\lambda_{g,f}\right\}_{g=5,6}, \left\{\lambda_{g,L}\right\}_{g=1:6}, \left\{\lambda_{g,f}\right\}_{g=1:6} \right)$$

Growth, maturity, selectivity, and proportion retained at age

SL.10 $$L_{a,x} = L_{\infty,x}\left(1 - e^{-k_x a}\right)$$

SL.11 $$w_{a,x} = c_1 L_{a,x}^{c_2}$$

SL.12 $$m_a = \left(1 + \exp\left[-\log(19)\left(a - \tilde{A}_{50}\right) / \left(\tilde{A}_{95} - \tilde{A}_{50}\right)\right]\right)^{-1}$$

SL.13

$$S_{g,f,a,c} \propto \left(1 + \exp\left[-\log(19)\left(L_{a,x} - \tilde{L}_{50,g,f,1}\right) / \left(\tilde{L}_{95,g,1} - \tilde{L}_{50,g,f,1}\right)\right]\right)^{-1} \times \left(1 + \exp\left[-\log(19)\left(L_{a,f} - \tilde{L}_{50,g,f,2}\right) / \left(\tilde{L}_{95,g,2} - \tilde{L}_{50,g,f,2}\right)\right]\right)^{-1}$$

SL.14

$$P_{g,f,a,x} = \begin{cases} 0 & L_{a,x} < L_{\text{lim},f} \\ 1 & L_{a,x} \geq L_{\text{lim},f} \end{cases}$$

State dynamics

SL.15 $$R_0 = B_0 / \phi^{SSB}_{F=0}$$

SL.16

$$N_{1,a,x} = \begin{cases} 0.5\bar{R}e^{-M_x(a-1)-S_{g,1,a,x}F_{ini}+\delta_a} & 1 \leq a \leq A-1 \\ \dfrac{N_{1,a-1,x}}{\left(1 - e^{-M_x - S_{g,1,a,x}F_{ini}}\right)} e^{\delta_A} & a = A \end{cases}$$

SL.17 $$N_{t,1,x} = 0.5\bar{R}e^{\omega_t} \quad t > 1$$

Equations

SL.18
$$N_{t,a,x} = \begin{cases} N_{t-1,a-1,x} e^{-Z_{t-1,a-1,x}} & 2 \le a \le A-1 \quad t > 1 \\ N_{t-1,a-1,x} e^{-Z_{t-1,a-1,x}} + N_{t-1,a,x} e^{-Z_{t-1,a,x}} & a = A \quad t > 1 \end{cases}$$

SL.19
$$SSB_t = \sum_{a=1}^{A} m_a w_{a,f} N_{t,a,f}$$

SL.20
$$C_{t,g,a,x} = w_{a,x} N_{t,a,x} \frac{S_{g,t,a,x} F_{t,g} P_{g,t,a,x}}{Z_{t,a,x}} \left[1 - e^{-Z_{t,a,x}} \right]$$

SL.21
$$C_{t,g} = \sum_a C_{t,g,a,m} + \sum_a C_{t,g,a,f}$$

SL.22
$$Z_{t,a,x} = M_x + \sum_{g=1}^{G} S_{g,t,a,x} F_{t,g} \left(P_{g,t,a,x} + \left(1 - P_{g,t,a,x} \right) d_g \right)$$

Predicted observations

SL.23
$$\hat{I}_{t,g=2} = q_{g=2} \left(\sum_{a=1}^{A} S_{g=2,t,a,m} N_{a,t,m} + \sum_{a=1}^{A} S_{g=2,t,a,f} N_{a,t,f} \right)$$

$$\hat{I}_{t,g=3} = q_{g=3} \left(\sum_{a=1}^{A} w_{a,m} S_{g=3,t,a,m} N_{a,t,m} + \sum_{a=1}^{A} w_{a,f} S_{g=3,t,a,f} N_{a,t,f} \right)$$

SL.24
$$\hat{u}_{g,t,l,x+c} = \frac{\sum_a p_{a,l,x} N_{t,a,x} S_{g,t,a,x} P_{g,t,a,x}}{\sum_{l'} \sum_a p_{a,l',x} N_{t,a,x} S_{g,t,a,x} P_{g,t,a,x}}$$

SL.25
$$\hat{u}_{g,t,l,x-c} = \frac{\sum_a \left(p_{a,l,m} N_{t,a,m} S_{g,t,a,m} + p_{a,l,f} N_{t,a,f} S_{g,t,a,f} \right)}{\sum_{l'} \sum_{a'} \left(p_{a',l',m} N_{t,a',m} S_{g,t,a',m} + p_{a,l',f} N_{t,a',f} S_{g,t,a',f} \right)}$$

SL.26
$$\hat{f}_{g,t,l,f} = \frac{\sum_a p_{a,l,f} N_{t,a,f} S_{g,t,a,f} P_{g,t,a,f}}{\sum_{a'} \sum_{x=m,f} p_{a',l,x} N_{t,a',x} S_{g,t,a',x} P_{g,t,a',x}}$$

Table 4. Negative log-posterior (G) computation based on negative log-likelihood functions for biomass indices (ℓ_I), length composition data (ℓ_L), proportion female-at-length (ℓ_f), and negative log-prior distributions for recruitment (ℓ_R), stock-recruitment steepness (ℓ_h) and natural mortality (ℓ_M).

Equations	
SL.26	$z_{g,i} = \log\left(\frac{I_{g,i}}{\hat{I}_{g,i}}\right)$
SL.27	$\widehat{\log q_g} = \frac{1}{n_{g,I}} \sum_{i=1:n_{g,I}} z_{g,i}$
SL.28	$Z_{g,I} = \sum_{i=1:n_{g,I}} \left(z_{g,i} - \widehat{\log q_g}\right)^2$
SL.29	$Z_R = \sum_{t=2:T} \omega_t^2 + \sum_{a=1:A} \delta_a^2$
SL.30	$Z_{g,f} = \sum_{t=1:T} \sum_{l=1:n_{g,t,t,x}} \log\left(\hat{f}_{g,t,l,f} / f_{g,t,l,f}\right)^2$
SL.30	$\eta_{g,t,l,x} = \log p_{g,t,l,x} - \log \hat{u}_{g,t,l,x} - \frac{1}{n_{g,t,l,x}} \sum_{l=1:n_{g,t,l,x}} \left[\log p_{g,t,l,x} - \log \hat{u}_{g,t,l,x}\right]$
SL.31	$Z_{g,t,x} = \sum_{t=1:T} \sum_{l=1:n_{g,t,l,x}} \eta_{g,t,l,x}^2$
SL.32	$\hat{\tau}_{g,I}^2 = \frac{1}{\mathbf{n}_{g,I} - 1} Z_{g,I}$
SL.33	$\hat{\tau}_{g,t,x}^2 = \frac{1}{\mathbf{n}_{g,t,x} - T_{g,t,x}} Z_{g,t,x}$
SL.33	$\hat{\tau}_{g,f}^2 = \frac{1}{\mathbf{n}_{g,t,f} - 1} Z_{g,f}$
SL.34	$\ell_I = \sum_{g=5,6} \lambda_{g,I} \mathbf{n}_{g,I} \log\left(\hat{\tau}_{g,I}^2\right)$
SL.35	$\ell_L = \sum_{x=m,f,c} \sum_{g=1:6} \lambda_{g,t} \left(\mathbf{n}_{g,t,x} - T_{g,t,x}\right) \log\left(\hat{\tau}_{g,t,x}^2\right)$
SL.36	$\ell_f = \sum_{g=1:6} \lambda_{g,f} \mathbf{n}_{g,t,f} \log\left(\hat{\tau}_{g,f}^2\right)$

Equations

SL.36 $$\ell_R = \frac{1}{2\sigma_R^2} Z_R$$

SL.37 $$\ell_h = -\left[(\beta_1 - 1)\log h + (\beta_2 - 1)\log(1-h)\right]$$

SL.38 $$\ell_M = \frac{1}{2\sigma_M^2}\left(\left(M_m - \mu_M^m\right)^2 + \left(M_f - \mu_M^f\right)^2\right)$$

SL.39 $$G = \ell_I + \ell_L + \ell_f + \ell_R + \ell_h + \ell_M$$

Note: Parameters (β_1, β_2) in the stock-recruitment steepness prior (LP.12) are derived from the mean and standard deviation parameters in the following steps: (1) $\alpha_1 = 1.25\mu_h - 0.25$; (2) $\alpha_2 = \frac{\alpha_1(1-\alpha_1)}{1.5625\sigma_h^2} - 1$; (3) $\beta_1 = \alpha_1\alpha_2$; (4) $\beta_2 = \alpha_2(1-\alpha_1)$.

Table 5. Estimated standard errors for SCAL model fits to length composition data. Values are based on a multivariate-logistic likelihood function for four fisheries and two surveys (LL.3 - longline NAFO Divisions 3NOPs; LL.4 - longline NAFO Divisions 4VWX5Zc; OT.3 - otter trawl NAFO Divisions 3NOPs; RV- DFO 4VWX RV trawl survey; HS - 3DFO-Industry Halibut Survey).

Composition	LL.3	LL.4	OT.3	OT.4	RV	HS
Males	0.544	0.638	0.812	0.770	0.745	0.525
Females	0.368	0.351	0.661	0.604	0.579	0.285
Combined	0.336	0.411	0.812	0.655	0.509	0.331

Table 6. Summary of the harvest strategies evaluated. Three fixed TAC strategies and five F strategies were evaluated with and without an increase in minimum legal size and with and without voluntary release of halibut greater than 167 cm. A minimum size of 81 cm with no voluntary release is the status quo harvest control. The figures and tables where the results are presented in this document are indicated.

	Harvest Strategies			
Min size:	81 cm	81 cm	85 cm	85 cm
Voluntary Release greater than167 cm:	no	yes	no	yes
Fixed TAC				
TAC=2.4	Table 10, Figure 11	Figure 11	Figure 11	Figure 11
TAC=2.6	Table 10	not presented	not presented	not presented
TAC=2.8	Table 10	not presented	not presented	not presented
F strategies[1]				
F=0.10	Table 10, Figure 12	Figure 12	Figure 12	Figure 12
F=0.125	Table 10	not presented	not presented	not presented
F=0.14	Table 10, Figure 15	not presented	not presented	not presented
F=0.15	Table 10, Figure 13	Figure 13	Figure 13	Figure 13
F=0.20	Table 10, Figure 14	Figure 14	Figure 14	Figure 14

[1] *Change (up or down) of TAC between years less than 15%.*

Table 7. Notation for the Atlantic halibut operating model (HAL). Note cells with dashes indicate empty cells.

Symbol	Value	Description
T_1	47	Year in which the management procedure begins
T_2	83	Total number of years to simulate
A	35	Number of operating model age-classes
G	6	Number of fisheries (surveys count as fisheries)
t	1,2,...,T	Time step ($T = T_1$ for conditioning, $T = T_2$ for simulating)
a	1,2,...,A	Age-class
x	m,f	Male (m), female (f) index
n_x	2	Number of sex classes
g	1,2,...G	Fishery/gear index
B_0		Unfished female spawning biomass (1,000s tonnes)
h	0.75	Stock-recruitment function steepness (fixed)
q_g	0.00479	Catchability coefficient for gear g
σ_R	0.25	Standard error of log-recruitment
γ_R	0.0	Lag-1 autocorrelation in log-recruitment deviations
M	0.15,0.15	Estimated and Fixed natural mortality rates, respectively (/yr)
L_1^∞	-	Asymptotic length (cm) for class x
k_x	0.18,0.12	von Bertalanffy growth constant for males, females, respectively
c_1, c_2	0.00673, 3.12	length-weight coefficients (weight converted to tonnes within HAL)
$\tilde{A}_{50}$, $\tilde{A}_{95}$	8.5, 11.5	Age-at-50% and -95% maturity
$\tilde{L}_{\lim}$	81, 85	Minimum size limit (cm)
$\tilde{L}^{C}_{50,g,1}$, $\tilde{L}^{C}_{95,g,1}$	See SCAL	Length-at-50% and -95% selectivity: ascending limb
$\tilde{L}^{C}_{95,g,2}$, $\tilde{L}^{C}_{50,g,2}$	See SCAL	Length-at-95% and -50% selectivity: descending limb
$\tilde{L}^{D}_{95,g}$, $\tilde{L}^{D}_{50,g}$	See SCAL	Length-at-50% and -95% discard probability
$\pi_{1,x}$	0.5, 0.5	Proportion of age-1 recruits assigned to sex class x
d_g	0.26, 1.26	discard mortality rates for LL and OT, respectively (/yr)
$L_{a,1}$	-	Length-class of sex-x at age-a (cm)

Symbol	Value	Description
$w_{a,l}$	-	Weight-at-age for fish in class *x*
m_a	-	Proportion female mature-at-age
$P_{a,l,g}$	-	Proportion of age-*a*, sex-*x* discarded at-sea
$S_{a,l,g}$	-	Selectivity for age-*a*, sex-*x* by gear-*g*
$\boldsymbol{R_0}$	-	Unfished equilibrium recruitment
$\phi_{\tilde{\mathbf{F}}}^{\mathrm{SSB}}$	-	Spawning biomass per recruit given vector $\tilde{\mathbf{F}}$
ϕ_g^{L}	-	Landed yield per recruit for gear-*g*
ϕ_g^{D}	-	Discarded yield per recruit for gear-*g*
$N_{a,l,t}$	-	Number of age *a* fish in sex-*x* in year *t*
$\omega_{R,t}$	-	Auto-correlated log-normal recruitment process deviation
B_t	-	Spawning biomass in year *t*
$C_{a,l,g}$	-	Landed catch-at-age in fishery *g*
$D_{a,l,g}$	-	At-sea discards-at-age fishery *g*
$F_{t,g}$	-	Fishing mortality rate for gear *g* in year *t*
$Z_{a,l,t}$	-	Total mortality rate for age-*a*, sex-*x* in year *t*
$I_{t,g}$	-	Model biomass index for gear *g* (only HS simulated)
$\hat{I}_{t,g}$	-	Observed biomass index for gear *g* (only HS simulated)
$u_{a,l,g}^{\mathrm{C}}$	-	Proportion of age-*a* in year *t* landed catch
$u_{a,l,g}^{\mathrm{D}}$	-	Proportion of age-*a* in year *t* dead discarded catch
δ_t	$N(0,1)$	Standard normal error in log-recruitment
$\varepsilon_{t,g}$	$N(0,1)$	Standard normal error for biomass index *g*

Table 8. HAL model specifications. Equations sequentially define the population dynamics and simulated observations for a set of input parameters derived from the SCAL framework assessment model.

	Equations
Growth, maturity, and selectivity	
OM.1	$L_{a,x} = L_x^{\infty}\left(1-e^{-k_x a}\right)$
OM.2	$w_{a,x} = c_1 L_{a,x}^{c_2}$
OM.3	$m_a = \left(1+\exp\left[-\log(19)\left(a-\tilde{A}_{50}\right)/\left(\tilde{A}_{95}-\tilde{A}_{50}\right)\right]\right)^{-1}$
OM.4	$S_{a,x,g} \propto \left(1+\exp\left[-\log(19)\left(L_{a,x}-\tilde{L}^{\mathrm{asc}}_{50,g,1}\right)/\left(\tilde{L}^{\mathrm{asc}}_{95,g,1}-\tilde{L}^{\mathrm{asc}}_{50,g,1}\right)\right]\right)^{-1} \times\left(1+\exp\left[-\log(19)\left(L_{a,x}-\tilde{L}^{\mathrm{dsc}}_{50,g,2}\right)/\left(\tilde{L}^{\mathrm{dsc}}_{95,g,2}-\tilde{L}^{\mathrm{dsc}}_{50,g,2}\right)\right]\right)^{1}$
OM.5	$P_{a,x,g} = \begin{cases} 1.0 & L_{a,x} < L_{\mathrm{lim}} \\ \left(1+\exp\left[-\log(19)\left(L_{a,x}-\tilde{L}^{\mathrm{D}}_{50,g}\right)/\left(\tilde{L}^{\mathrm{D}}_{95,g}-\tilde{L}^{\mathrm{D}}_{50,g}\right)\right]\right)^{-1} & L_{a,x} \geq L_{\mathrm{lim}} \end{cases}$
State dynamics	
OM.6	$R_0 = B_0 / \phi^{\mathrm{SSB}}_{\bar{F}=0}$
OM.7	$N_{a,x,1} = \tilde{N}_{a,x,1998}$
OM.8	$\omega_{R,t} = \begin{cases} \dfrac{\sigma_R}{\sqrt{1-\gamma_R^2}}\delta_t & t=1 \\ \gamma_R \omega_{R,t-1} + \sigma_R \delta_t & t>1 \end{cases}$
OM.9	$N_{1,x,t} = 0.5\bar{R}e^{\omega_{R,t}-0.5\sigma_R^2/\left(1-\gamma_R^2\right)}$
OM.10	$N_{a,x,t} = \begin{cases} N_{a-1,x,t-1}e^{-Z_{a-1,x,t-1}} & 2 \leq a \leq A-1 \\ N_{a-1,x,t-1}e^{-Z_{a-1,x,t-1}} + N_{a,x,t-1}e^{-Z_{a,x,t-1}} & a = A \end{cases}$
OM.11	$B_t = \sum_{a=1}^{A} m_a w_{a,f} N_{a,f,t}$
OM.12	$C_{a,t,g} = \sum_{x=m,f} w_{a,x} N_{a,x,t} \dfrac{S_{a,x,g} F_{t,g}(1-P_{a,x,g})}{Z_{a,x,t}}\left[1-e^{-Z_{a,x,t}}\right]$
OM.13	$D_{a,t,g} = \sum_{x=m,f} w_{a,x} N_{a,x,t} \dfrac{S_{a,x,g} F_{t,g} P_{a,x,g}}{Z_{a,x,t}}\left[1-e^{-Z_{a,x,t}}\right]$
OM.14	$Z_{a,x,t} = M + \sum_{g=1}^{G} S_{a,x,g} F_{t,g}\left(d_g P_{a,x,g} - P_{a,x,g} + 1\right)$

Equations	
Observations	
OM.15	$I_{t,g} = q_g \sum_{a=1}^{A} \sum_{x=m,f} w_{a,x} S_{a,x,g} N_{a,x,t}$
OM.16	$\hat{I}_{t,g} = I_{t,g} \exp\left[\tau_{1,g} \varepsilon_{t,g} - \tau_{1,g}^2 / 2\right]$
OM.17	$u_{a,t,g}^{C} = C_{a,t,g} \Big/ \sum_{a'=1}^{A} C_{a,t,g}$

Table 9. Performance indicators (P.1-P.3) derived from the operating model (HAL) and used to compare closed-loop simulation outcomes to objectives for each candidate management procedure. The time steps t_1 and t_2 define the short (2014-2024), medium (2025-2035), and long (2036-2045) periods over which performance objectives are measured.

Eq.	Objective	Indicator	Probability or Statistic	Definition
P.1	Objective 1	Median of mean annual landed catch	Median average catch	$\text{median}\left(\overline{C^L} = \frac{1}{t_2 - t_1 + 1}\sum_{t_1}^{t_2} C_t^L\right)$
P.2	Objective2a	Proportion of projection years where spawning biomass is between B_{LIM} and B_{UPPER}	$P\left(B_{\text{LIM}} < B < B_{\text{UPPER}}\right)$	$P\left(B_{\text{LIM}} < B < B_{\text{UPPER}}\right) = \frac{\sum_{t_1}^{t_2} \mathrm{I}\left(B_{\text{LIM}} < B < B_{\text{UPPER}}\right)}{t_2 - t_1 + 1}$
P.3	Objective2b	Proportion of projection years where spawning biomass is greater than B_{UPPER}	$P\left(B > B_{\text{UPPER}}\right)$	$P\left(B > B_{\text{UPPER}}\right) = \frac{\sum_{t_1}^{t_2} \mathrm{I}\left(B > B_{\text{UPPER}}\right)}{t_2 - t_1 + 1}$

Table 10. Performance indicators from HAL simulations of constant TAC and constant F harvest strategies. Median average catch is measured over short, medium and long term, as well as the probability of being of being below B_{LIM} over 2 generations, the probability of being between B_{LIM} and B_{UPPER} and the probability of being in above B_{UPPER}. The probability of $B>B_{UPPER}$ is the probability of an increase in SSB as B_{UPPER} is the SSB is 2013.

Harvest Strategy	Median Average Catch			Probability in 2045		
	2014-2024	2025-2035	2036-2045	$B< B_{LIM}$	$B> B_{LIM}$ & $B<B_{UPPER}$	$B>B_{UPPER}$
TAC-2.4	2.40	2.40	2.40	0.00	0.01	0.99
TAC-2.6	2.59	2.60	2.60	0.01	0.07	0.92
TAC-2.8	2.80	2.80	2.80	0.04	0.18	0.77
F0.10[1]	3.52	2.73	2.22	0.01	0.11	0.88
F0.125[1]	4.06	2.67	2.23	0.02	0.53	0.44
F0.14[1]	4.30	2.63	2.18	0.13	0.60	0.27
F0.15[1]	4.42	2.61	2.09	0.23	0.57	0.20
F0.20[1]	4.91	1.81	1.81	0.47	0.26	0.27

[1] Change (up or down) of TAC between years less than 15%.

FIGURES

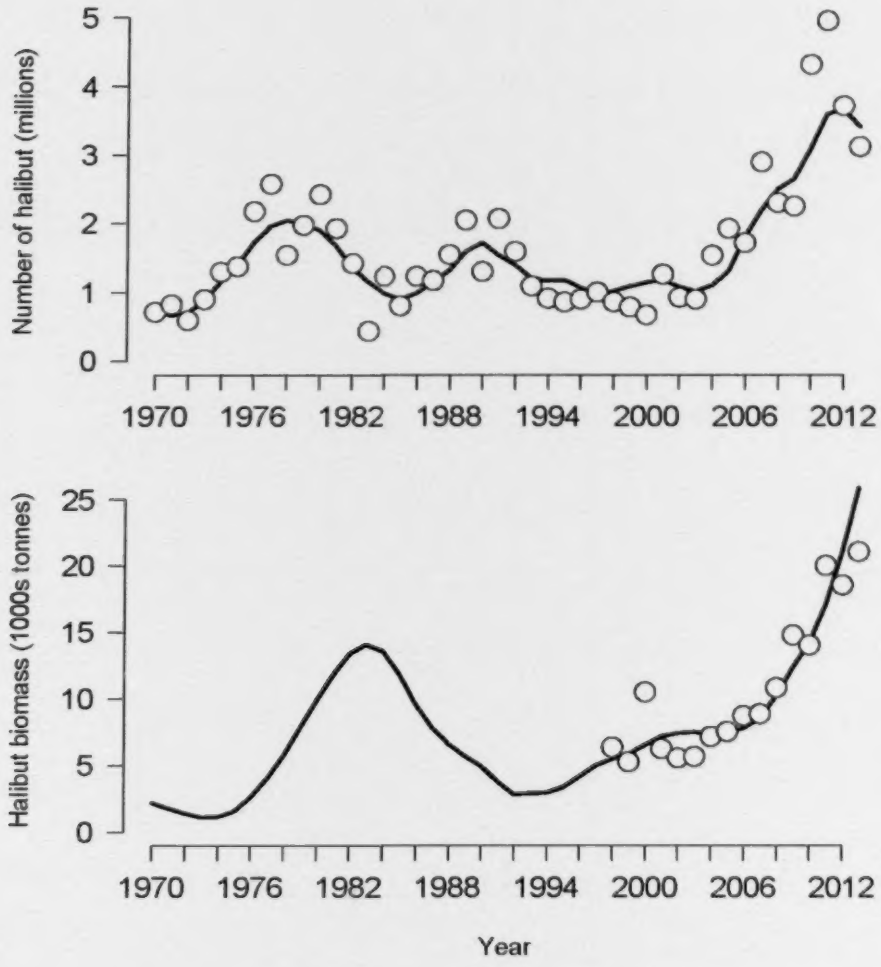

Figure 1. SCAL model fits to 4VWX RV survey (top) and DFO-Industry halibut longline survey (bottom).

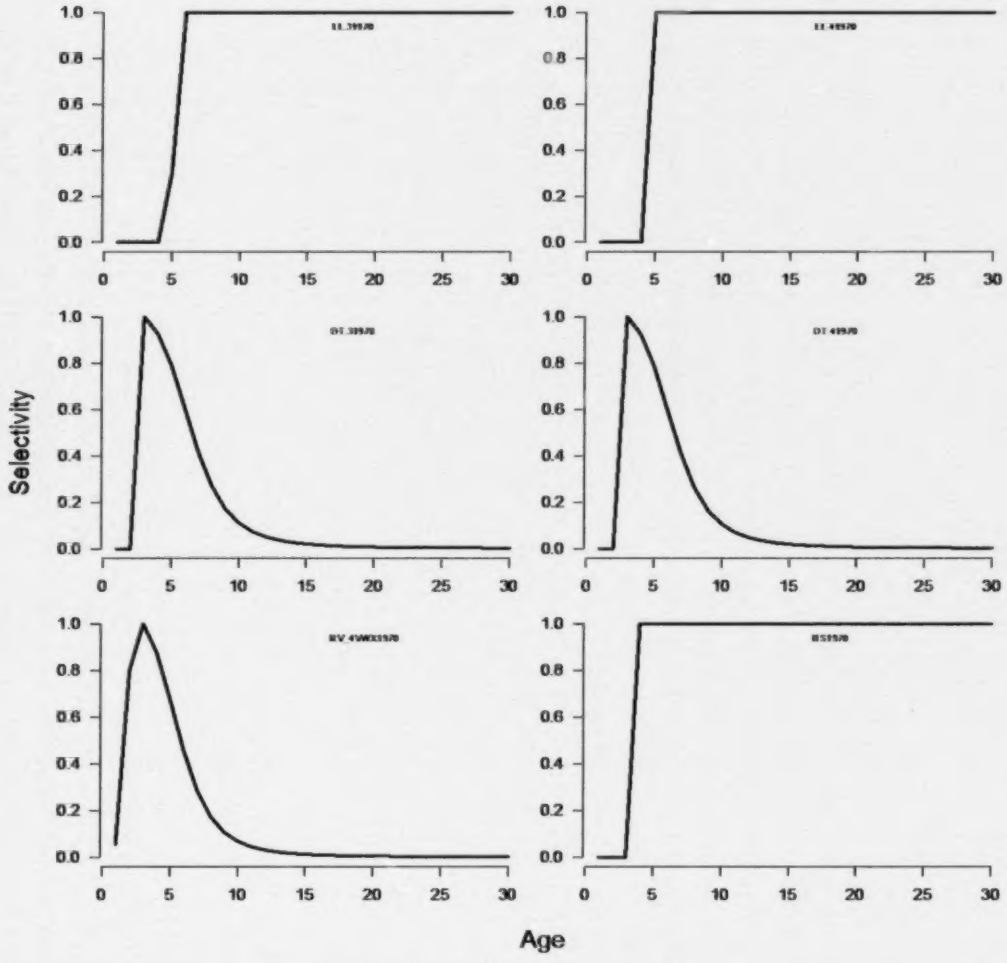

Figure 2. Selectivity-at-age estimated using the SCAL model for the long line fisheries in NAFO 3 and 4 (top row),otter trawl fishery in NAFO 3 and 4 (middle row) and the DFO RV survey in 4VWX and the 3NOPs4VWX Longline Halibut Survey (bottom row).

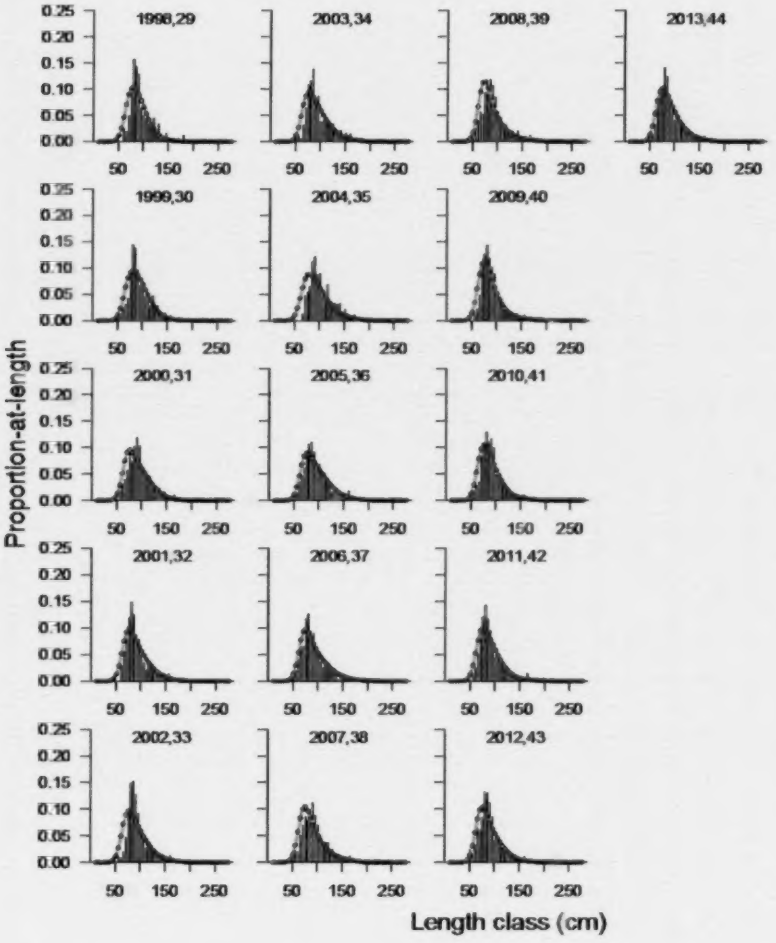

Figure 3a. SCAL model fits to DFO-Industry halibut survey length composition, sexes combined, 1998-2013.

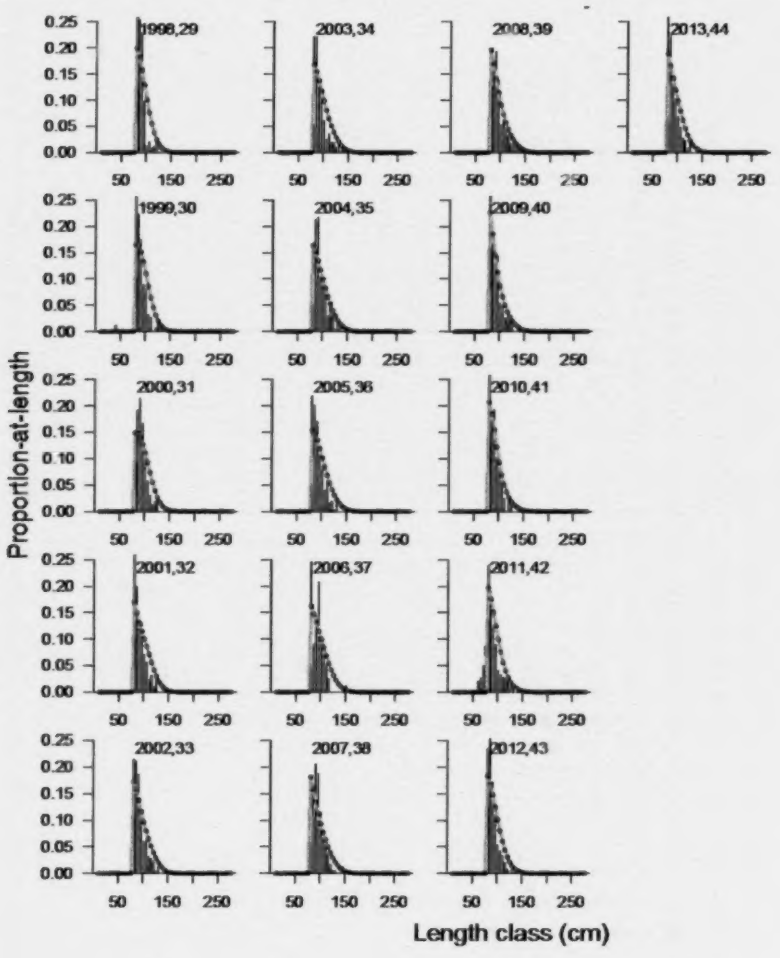

Figure 3b. SCAL model fits to DFO-Industry halibut survey length composition, males, 1998-2013.

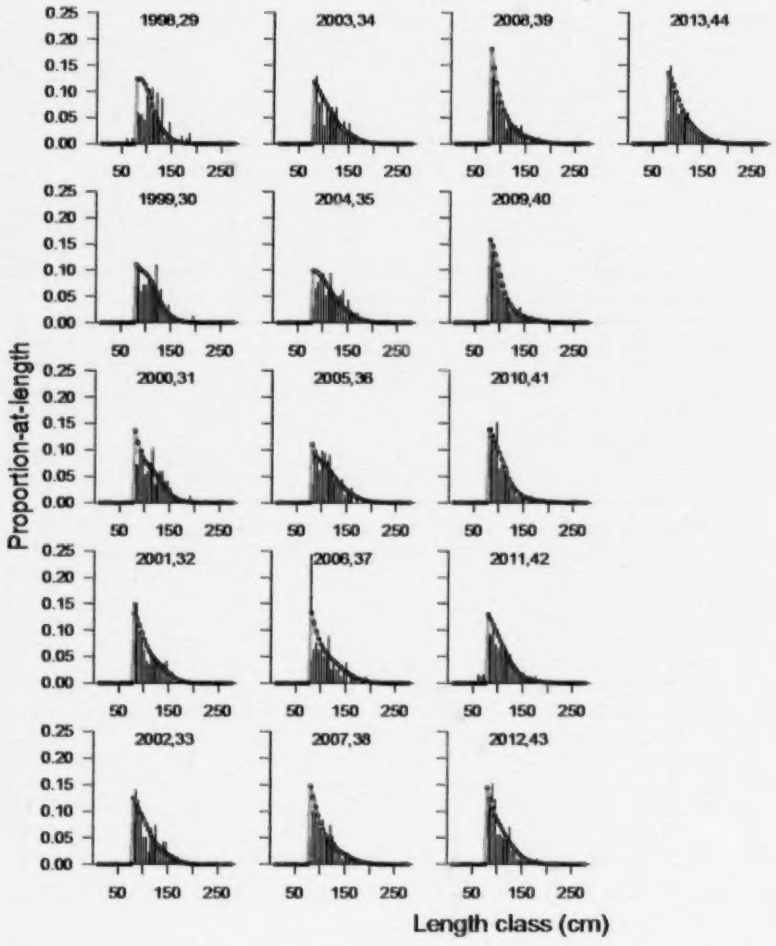

Figure 3c. SCAL model fits to DFO-Industry halibut survey length composition, females, 1998-2013.

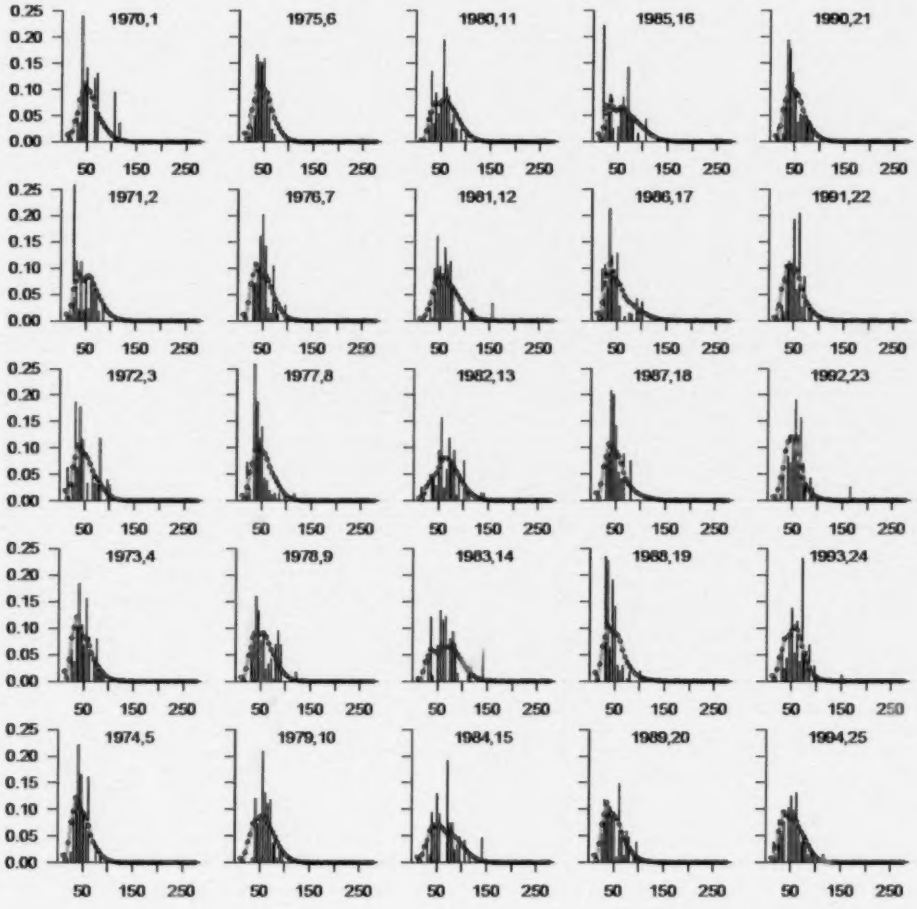

Figure 4a.1. SCAL model fits to 4VWX RV survey length composition, sexes combined, 1970-1994.

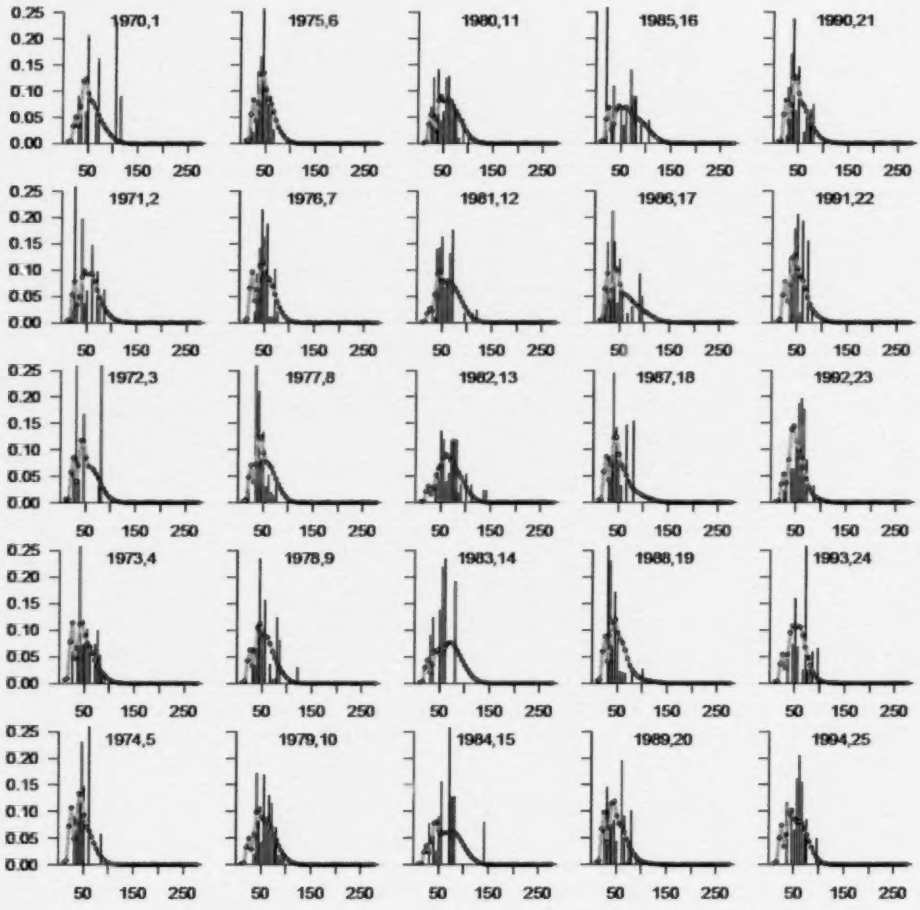

Figure 4b.1. SCAL model fits to 4VWX RV survey length composition, males, 1970-1994.

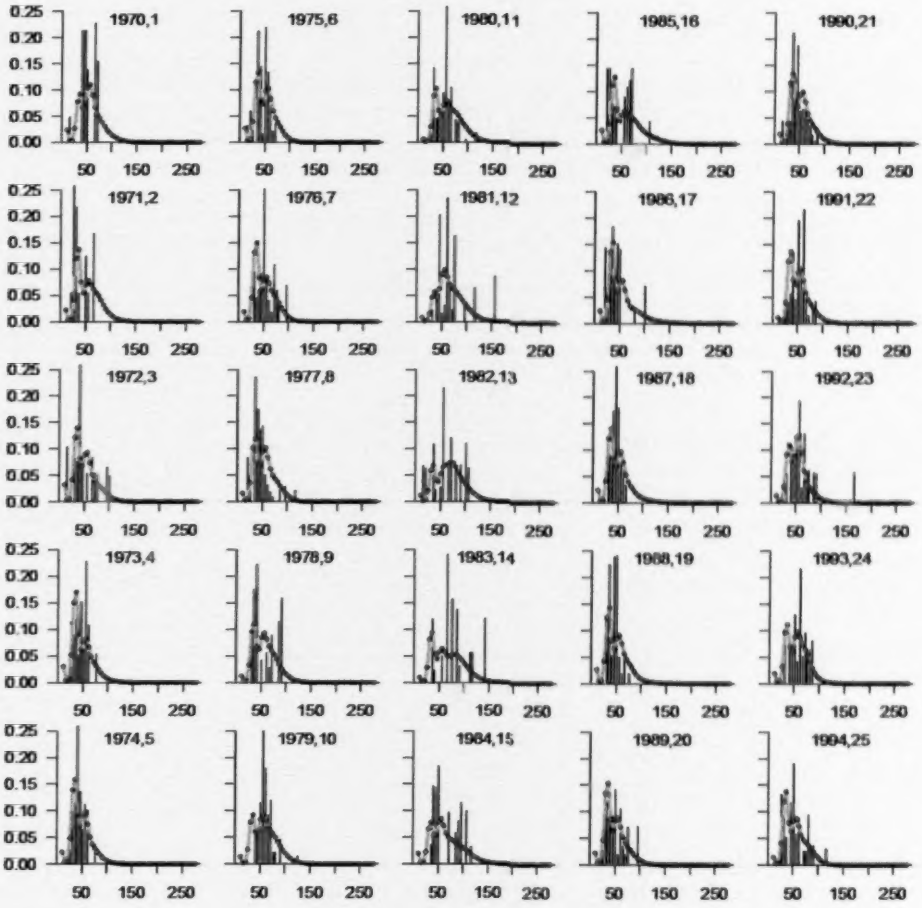

Figure 4c.1. SCAL model fits to 4VWX RV survey length composition, females, 1970-1994.

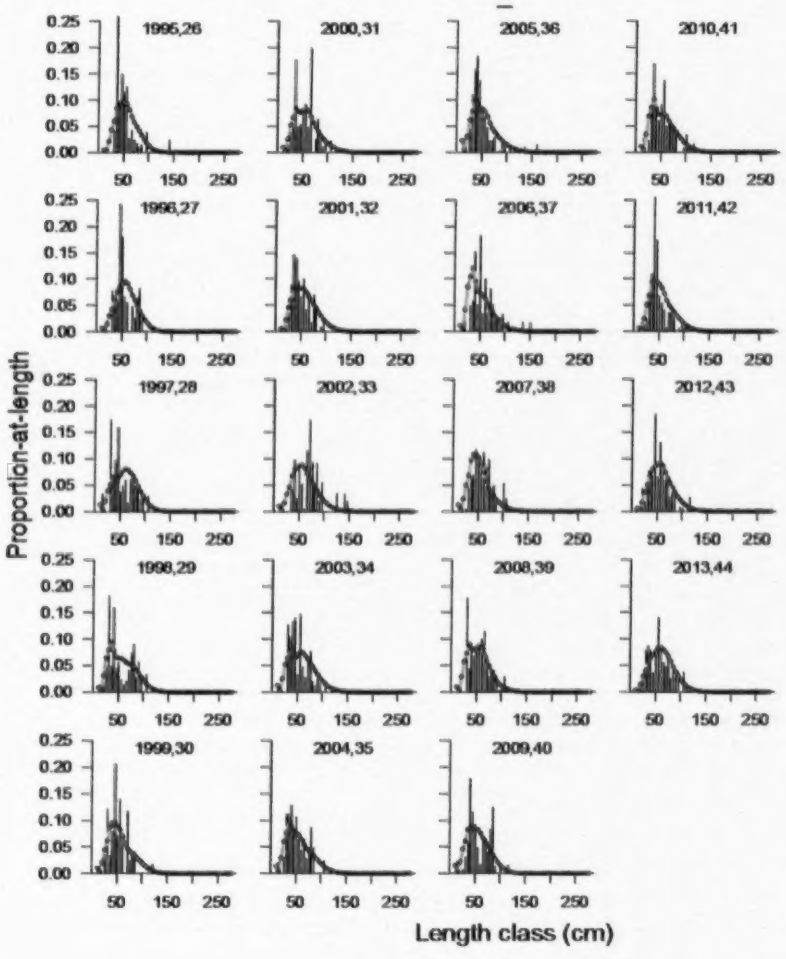

Figure 4a.2. SCAL model fits to 4VWX RV survey length composition, sexes combined, 1995-2013.

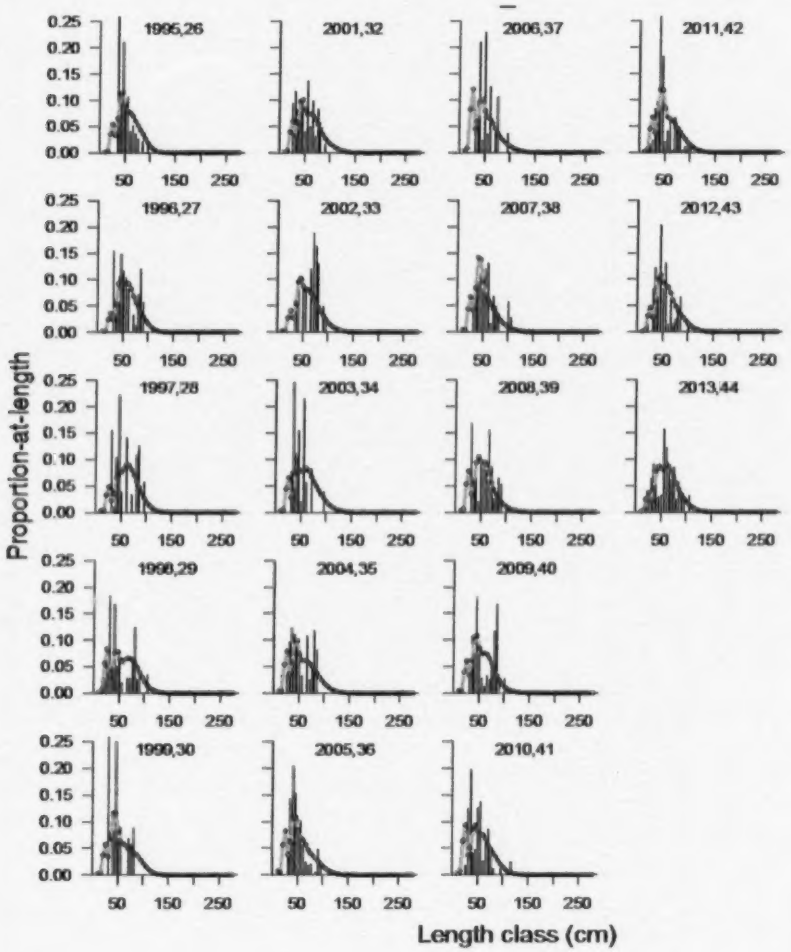

Figure 4b.2. SCAL model fits to 4VWX RV survey length composition, males, 1995-2013.

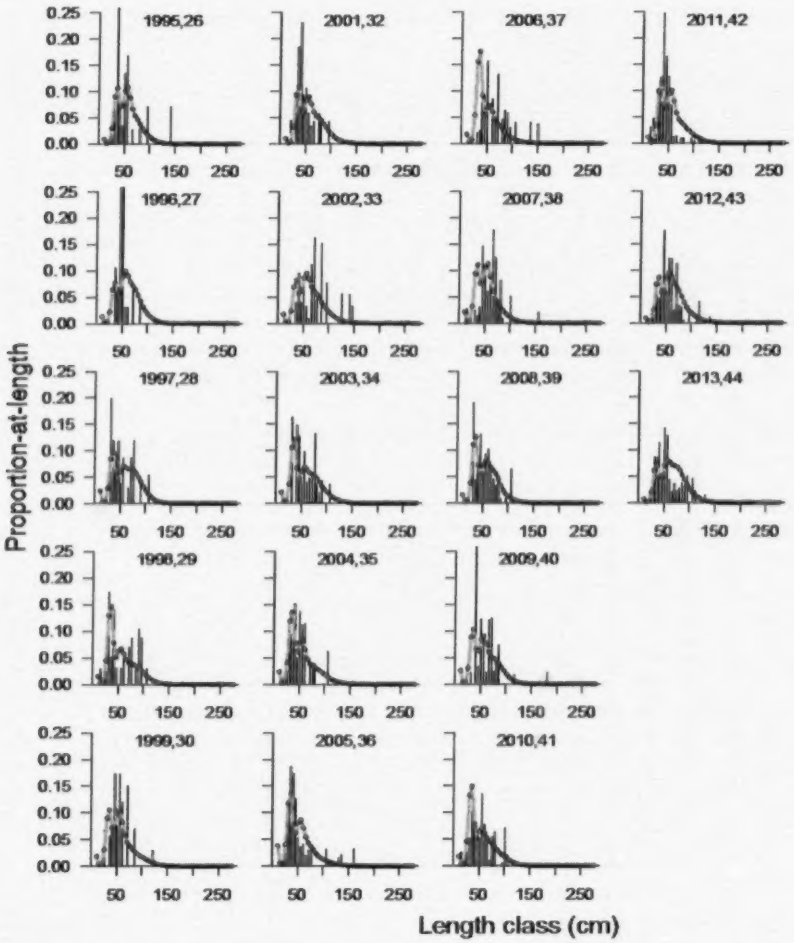

Figure 4c.2. SCAL model fits to 4VWX RV survey length composition, females, 1995-2013.

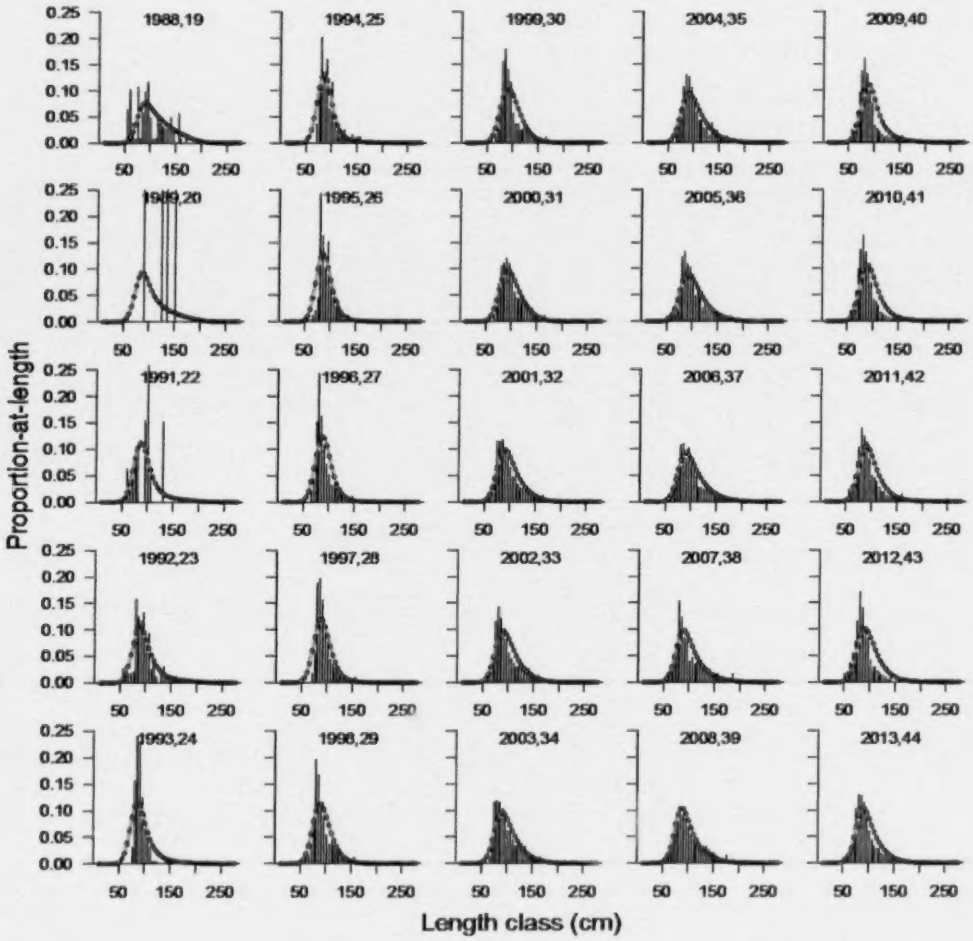

Figure 5a. SCAL model fits to commercial 4VWX longline fishery length composition, sexes combined, 1988-2013.

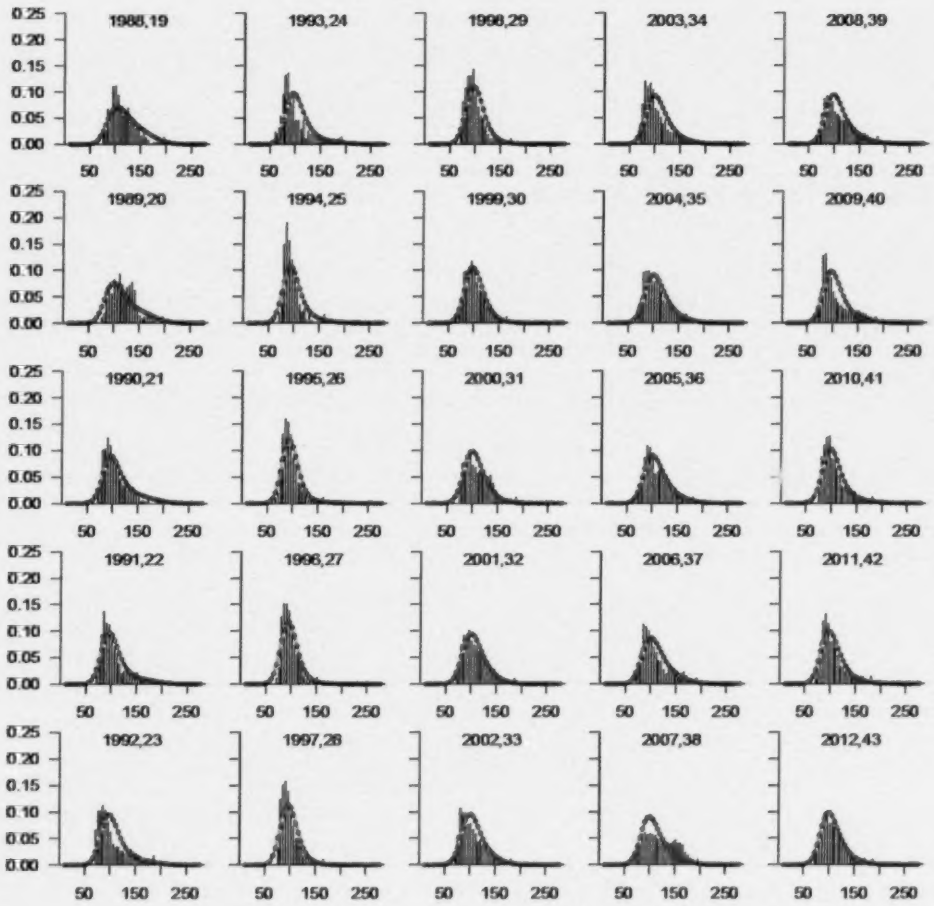

Figure 5b. SCAL model fits to commercial 3PNO longline fishery length composition, sexes combined, 1988-2012.

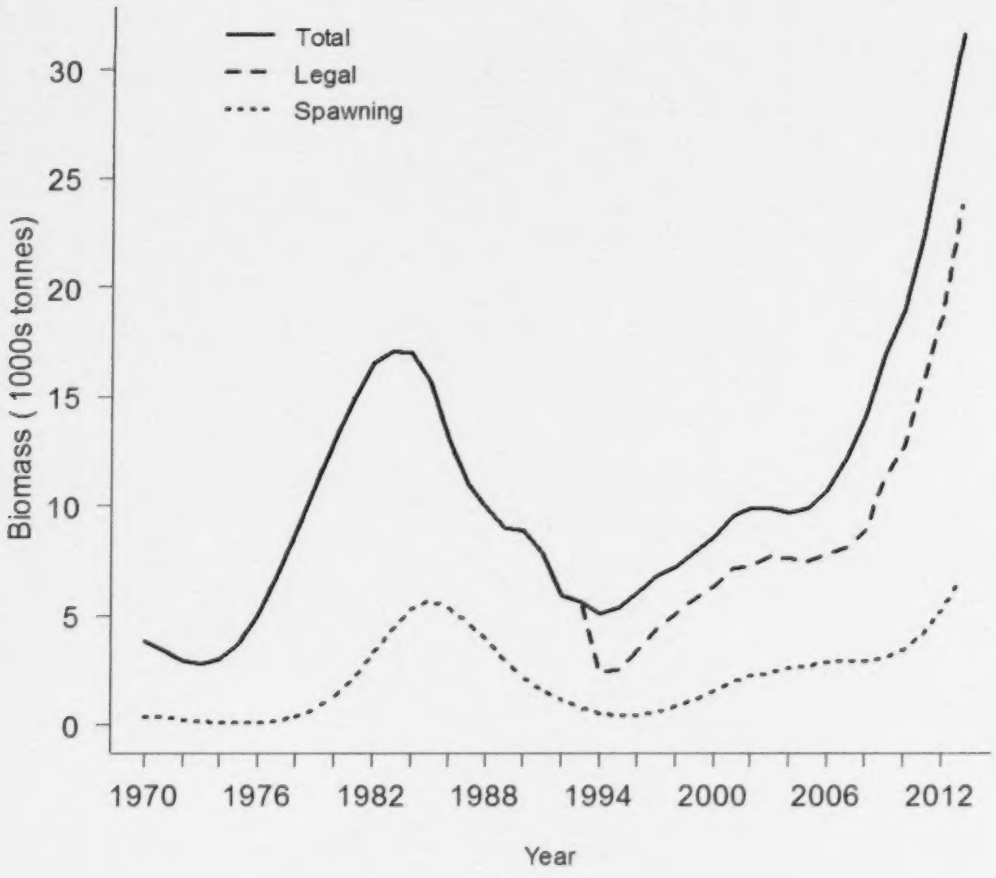

Figure 6. Estimated total (solid), legal-sized (dashed), and spawning stock (dotted) biomass.

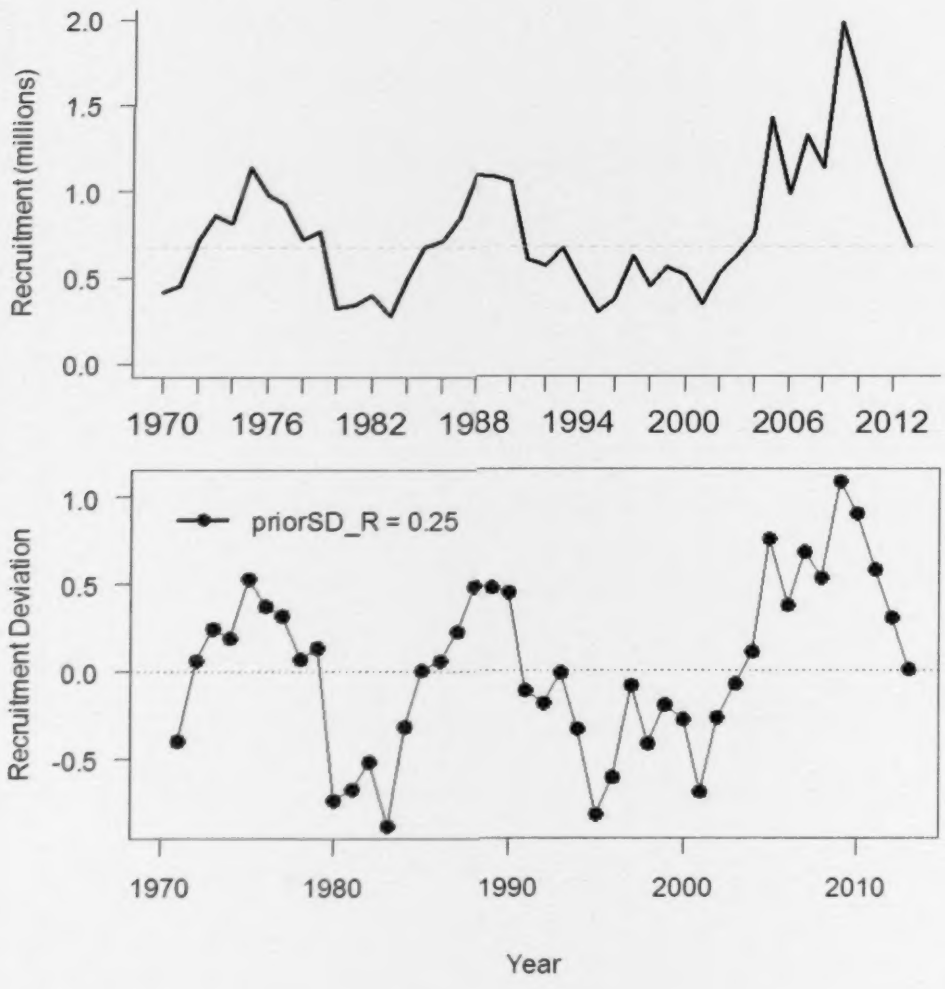

Figure 7. Estimated age-1 halibut recruitment and log-recruitment deviations about the estimated long-term average (bottom).

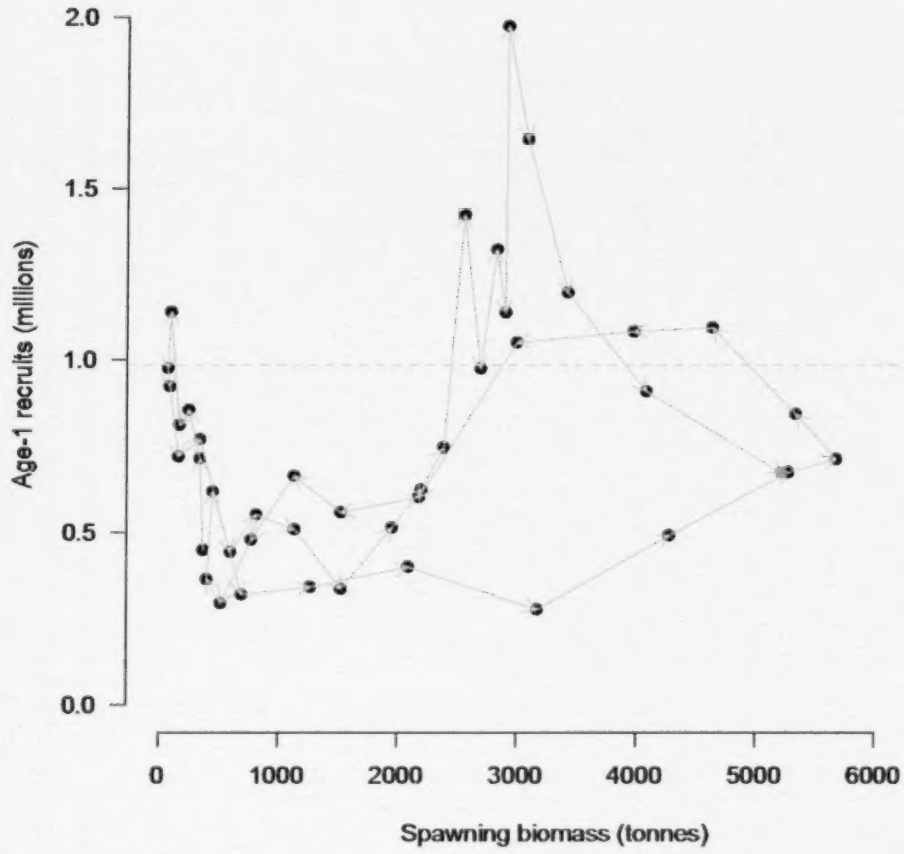

Figure 8. Relationship between age-1 halibut recruitment and the estimated spawning stock biomass in the previous year. The 2013 combination is shown as a red dot, while 50% of maximum recruitment is indicated by the horizontal dashed line. The arrows trace the historical pattern of biomass and recruitment over time.

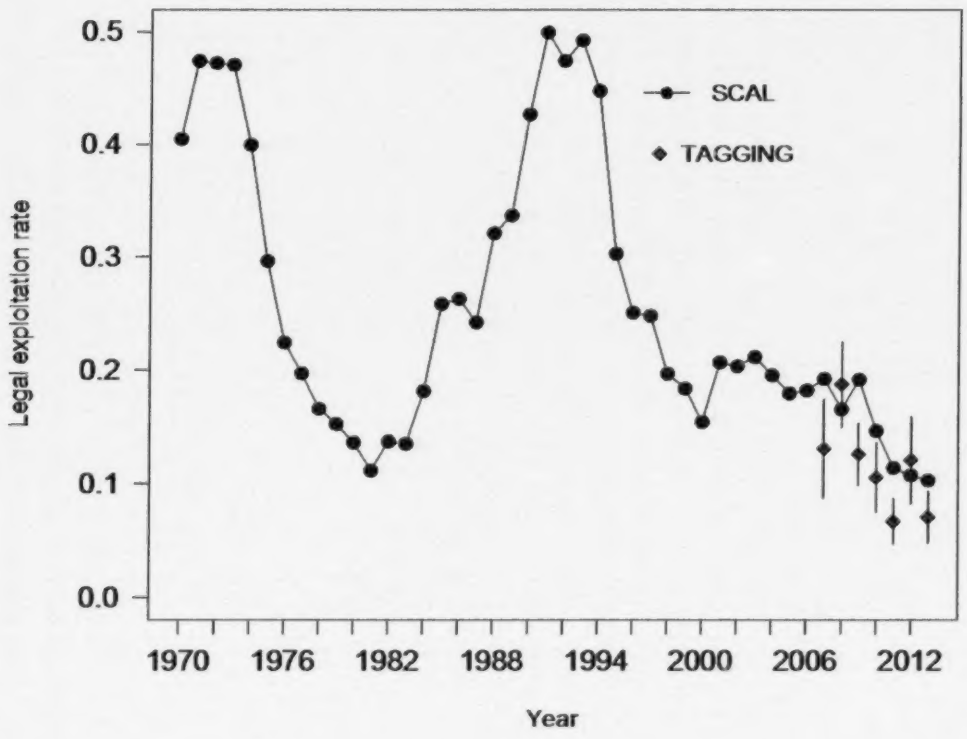

Figure 9. Estimated annual exploitation rates on legal-sized halibut and exploitation rate estimates derived from the halibut tagging program (diamonds, +/- 2 std errors of the estimates). All fish are assumed legal prior to 1988 and only fish larger than 81 cm thereafter.

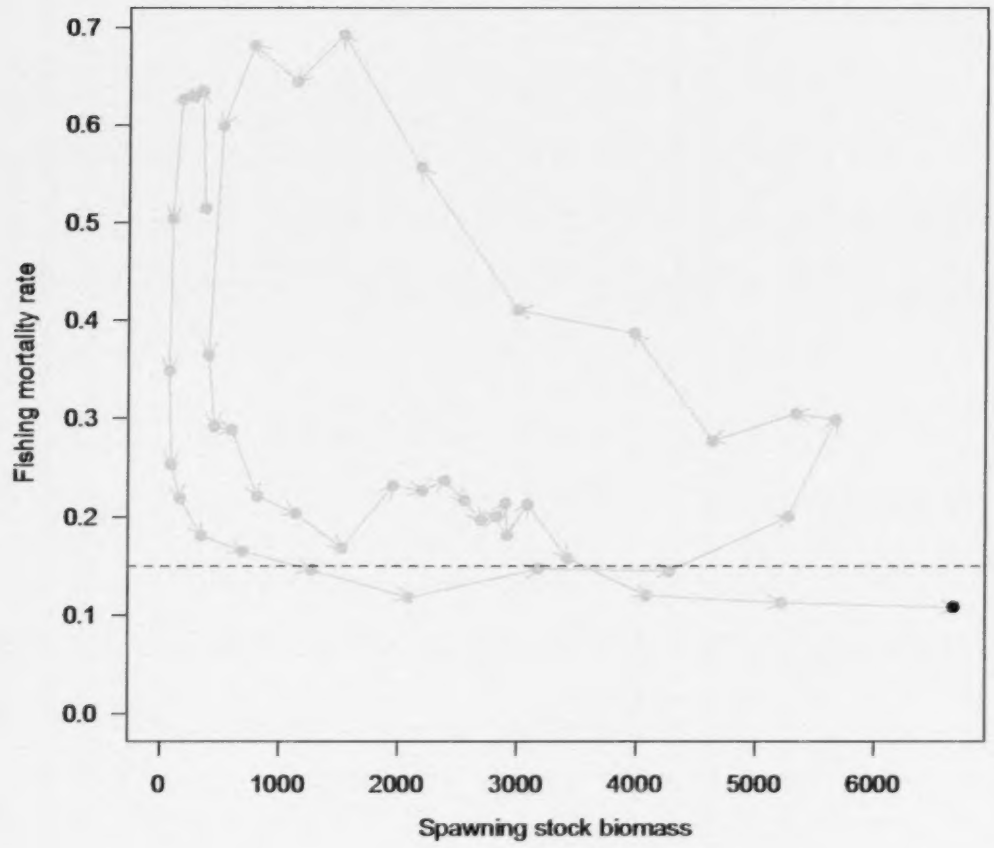

Figure 10. Instantaneous fishing mortality relationship to spawning stock biomass (tonnes). Vertical reference lines give possible biological reference points corresponding to 0.4 and 0.8 BMSY (assuming B_{MSY} approximately $0.35SSB_0$), while the horizontal reference line is where fishing mortality is equal to the female halibut natural mortality rate ($M_f = 0.149$). This relationship could be revised based on reference points estimated within SCAL (currently stock-recruitment parameters are not estimated).

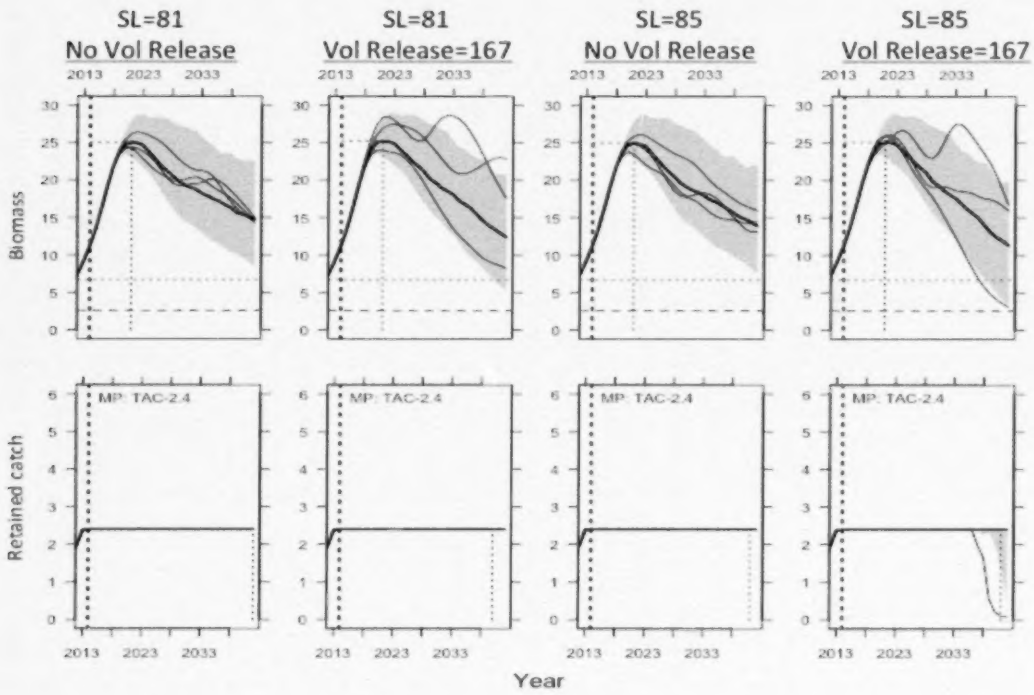

Figure 11. Simulated spawning stock biomass (1000s tonnes; top panels) and landed catch (1000s tonnes; bottom panels) for four harvest strategies based on constant 2,400 mt TAC combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut >167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

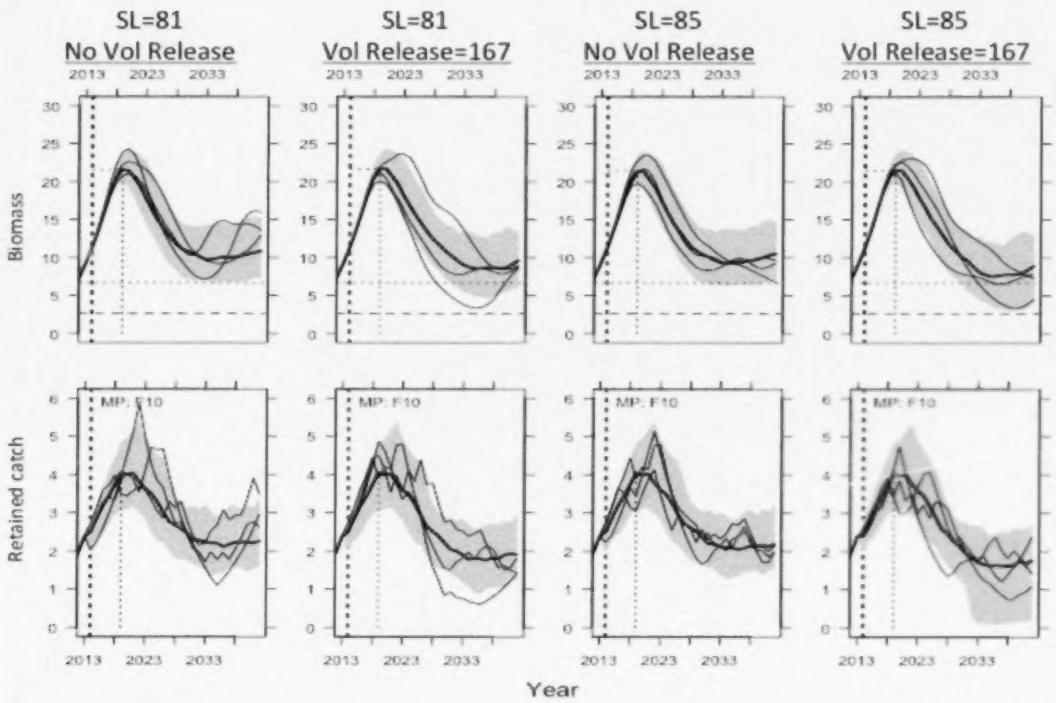

Figure 12. Simulated spawning stock biomass (1000s tonnes; top panels) and landed catch (1000s tonnes; bottom panels) for four harvest strategies based on constant F = 0.10 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

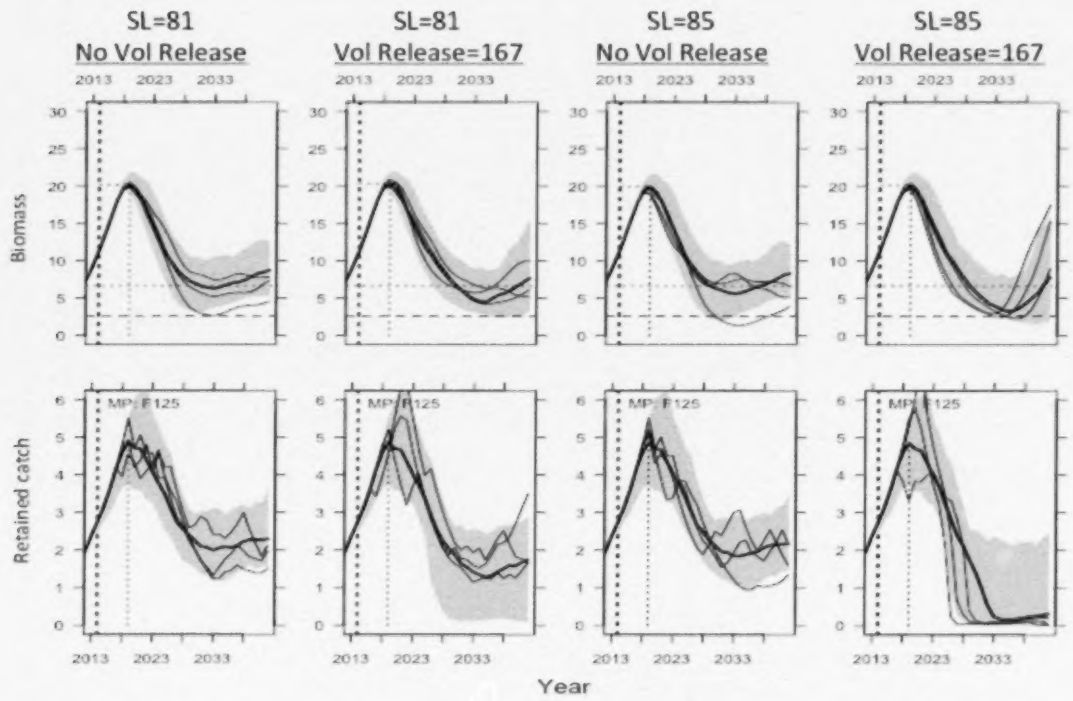

Figure 13. Simulated spawning stock biomass (1000s tonnes; top panels) and landed catch (1000s tonnes; bottom panels) for four harvest strategies based on constant F = 0.125 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

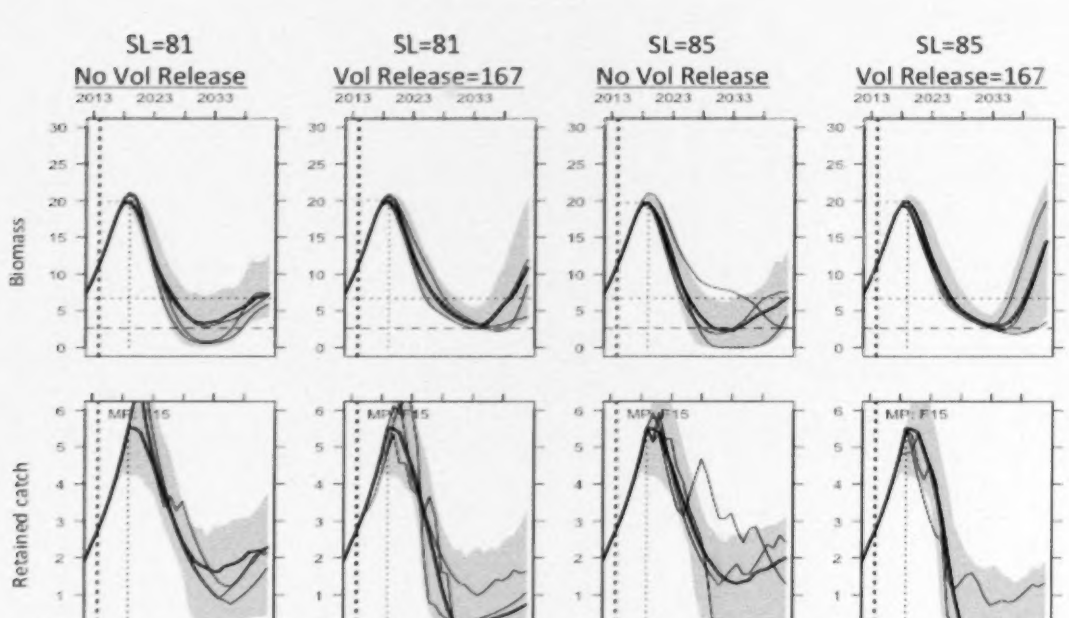

Figure 14. Simulated spawning stock biomass (1000s tonnes; top panels) and landed catch (1000s tonnes; bottom panels) for four harvest strategies based on constant F = 0.15 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

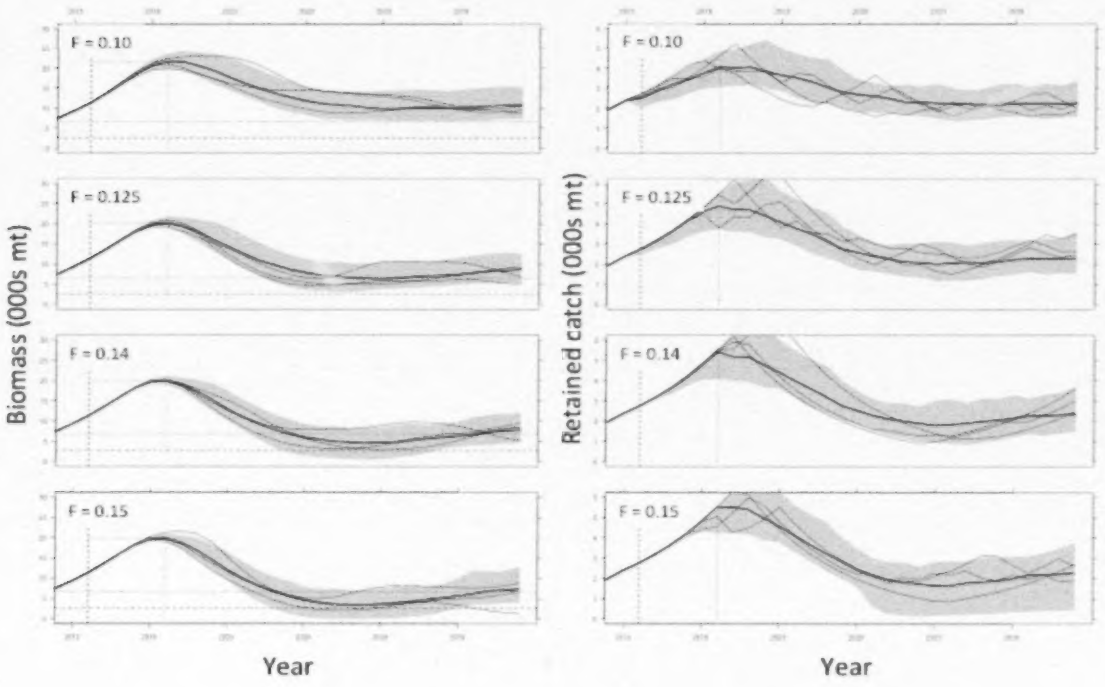

Figure 15. Simulated spawning stock biomass (1000s tonnes; left panels) and landed catch (1000s tonnes; right panels) for four harvest strategies based on constant fishing mortality rates F=0.10, 0.125, 0.14, and 0.15 with TAC changes of less than 15%. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). The median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates. Note the y-axis for the landed catch varies.

APPENDICES

APPENDIX 1: INDICES OF ABUNDANCE AND LANDINGS

Table A1.1 Halibut landings (mt) by NAFO Area and gear type. Foreign landings are included from 1970 to 2010. Only Canadian landings reported in 2011-2013.

Year	3NOP Longline	3NOP Otter Trawl	3NOP Other	4VWX Longline	4VWX Otter Trawl	4VWX Other
1970	257	442	0	553	229	48
1971	338	244	18	599	357	49
1972	211	319	0	634	129	67
1973	211	288	1	643	108	23
1974	158	315	49	539	66	49
1975	159	260	14	504	125	18
1976	152	241	0	530	152	29
1977	91	512	14	477	168	66
1978	82	261	17	662	261	167
1979	65	370	6	824	289	111
1980	82	221	6	982	392	83
1981	66	184	11	997	309	88
1982	83	426	31	1314	331	77
1983	154	141	173	1471	269	89
1984	637	323	130	1744	182	66
1985	916	955	205	1710	207	50
1986	937	759	54	1457	134	71
1987	639	805	8	1067	97	42
1988	784	264	7	1216	111	20
1989	647	164	18	1136	68	19
1990	626	490	9	1017	132	21
1991	296	803	136	802	131	18
1992	292	172	16	874	101	14
1993	268	117	31	758	134	12
1994	130	97	31	856	36	9
1995	161	86	38	520	47	1
1996	153	51	45	581	37	8
1997	175	75	125	692	34	4
1998	231	90	104	564	18	4
1999	227	148	57	585	27	7
2000	290	92	51	509	7	4
2001	430	159	88	739	31	2
2002	381	199	135	738	39	1
2003	336	267	192	748	53	4
2004	374	129	77	809	74	2
2005	354	68	80	771	62	1
2006	356	35	78	877	45	4
2007	517	37	32	889	85	2
2008	438	27	22	941	61	5
2009	395	484	40	1132	81	2
2010	431	115	52	1211	78	0
2011	318	28	37	1258	102	2
2012	460	27	52	1344	129	2
2013	520	30	16	1727	98	1

Table A1.2 Expanded numbers and standard error of Atlantic halibut caught in the DFO 4VWX RV survey.

Year	N Stratified Total	N Standard Error
1970	486875	156006
1971	560384	236453
1972	404199	94259
1973	612480	161044
1974	883968	248254
1975	938511	213616
1976	1484065	340713
1977	1757445	479994
1978	1051959	227131
1979	1348688	239834
1980	1652491	343813
1981	1316504	338349
1982	969238	253505
1983	298177	89303
1984	837621	223851
1985	546804	138342
1986	837143	272754
1987	795747	165929
1988	1053147	324327
1989	1393599	289572
1990	885333	192725
1991	1409158	342927
1992	1083879	280954
1993	742470	213111
1994	621322	131923
1995	583137	137046
1996	612809	164484
1997	680246	148371
1998	585949	145499
1999	533925	130956
2000	456952	99026
2001	857917	163143
2002	630739	123576
2003	611893	131909
2004	1046516	239926
2005	1311990	315899
2005	1125395	293945
2006	1171607	221118
2007	1971500	309567
2008	1568480	306106
2009	1533787	299849
2010	2941051	328487
2011	3378175	605403
2012	2529660	471812
2013	2124514	281664

Table A1.3 Index of legal-sized halibut abundance from the Industry-DFO longline halibut survey in 3NOPs4VWX predicted from GLM with lower and upper 95% confidence intervals (CI).

Year	GLM predicted	Lower CI	Upper CI
1998	31.59	16.22	61.53
1999	26.16	13.52	50.63
2000	52.17	27.14	100.29
2001	31.08	16.13	59.89
2002	27.62	14.33	53.23
2003	28.15	14.59	54.32
2004	35.60	18.50	68.50
2005	37.46	19.35	72.54
2006	43.33	22.40	83.82
2007	44.08	22.94	84.70
2008	53.81	28.06	103.20
2009	73.47	38.26	141.10
2010	69.78	36.36	133.93
2011	99.50	51.86	190.90
2012	92.24	48.07	177.01
2013	104.69	54.61	200.68

APPENDIX 2: RETROPSECTIVE PATTERNS

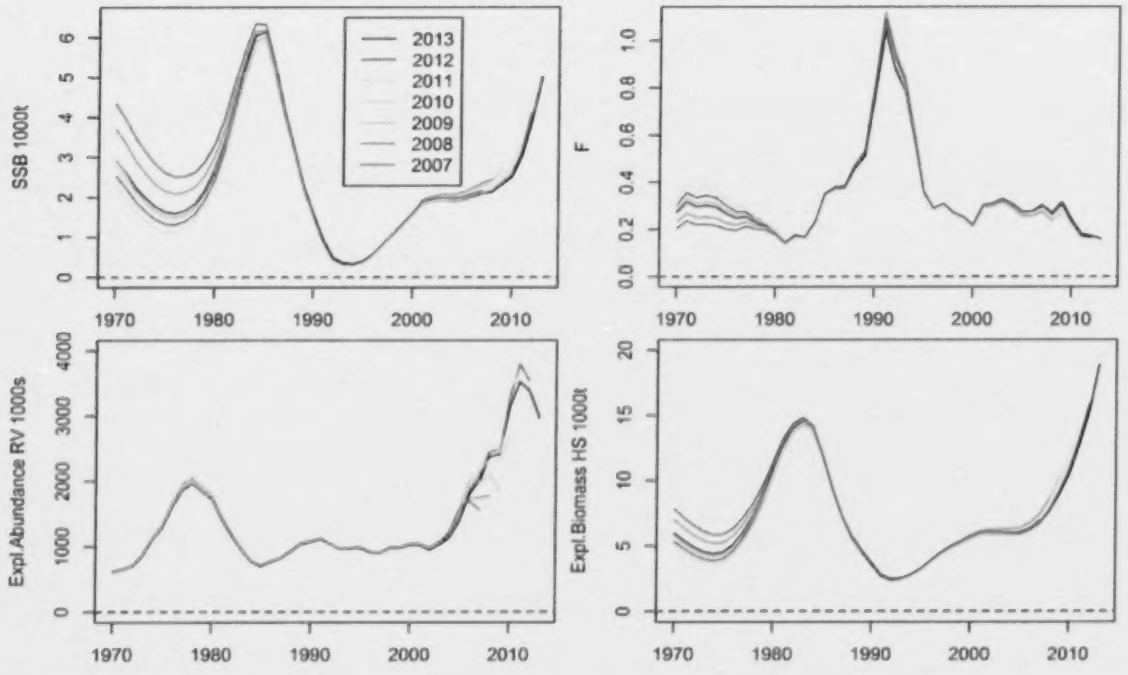

Figure A2.1. Retrospective patterns for estimated spawning stock biomass (SSB), fishing mortality (F), RV trawl survey abundance (Expl. Abundance RV) and exploitable biomass (Exploitable Biomass) from SCAL model.

APPENDIX 3: HAL SIMULATIONS WITH BEVERTON HOLT RECRUITMENT

Projection model (HAL) runs presented at the assessment meeting and used to evaluate relative risk of the harvest control strategies. Recruitment of age-1 individuals in each sex-class occurs on January 1st of the model year based on combining a deterministic Beverton-Holt stock-recruitment model with log-normally distributed, lag-1 auto-correlated random variation about the expected recruitment. These projections are another possible long-term trajectory for this stock.

Table A3.1. Performance indicators from HAL simulations of constant TAC and constant F harvest strategies. Median average catch is measured over short, medium and long term, as well as the probability of being of being below B_{LIM} over 2 generations, the probability of being between B_{LIM} and B_{UPPER} and the probability of being in above B_{UPPER}. The probability of $B>B_{UPPER}$ is the probability of an increase in SSB as B_{UPPER} is the SSB is 2013.

Harvest Strategy	Median Average Catch (1000s tonnes)			Probability in 2045		
	2014-2024	2025-2035	2036-2045	$B< B_{LIM}$	$B> B_{LIM}$ & $B<B_{UPPER}$	$B>B_{UPPER}$
TAC-2.4	2.40	2.40	2.40	0.02	0.18	0.80
TAC-2.6	2.59	2.60	2.60	0.16	0.25	0.59
TAC-2.8	2.80	2.80	2.80	0.42	0.34	0.25
F0.10[1]	2.34	2.46	2.34	0.00	0.01	0.99
F0.125[1]	2.73	2.51	2.39	0.00	0.33	0.67
F0.14[1]	2.92	2.47	2.36	0.01	0.61	0.37
F0.15[1]	3.04	2.45	2.32	0.04	0.71	0.25
F0.20[1]	3.52	2.10	1.87	0.72	0.28	0.00

[1] Change (up or down) of TAC between years less than 15%.

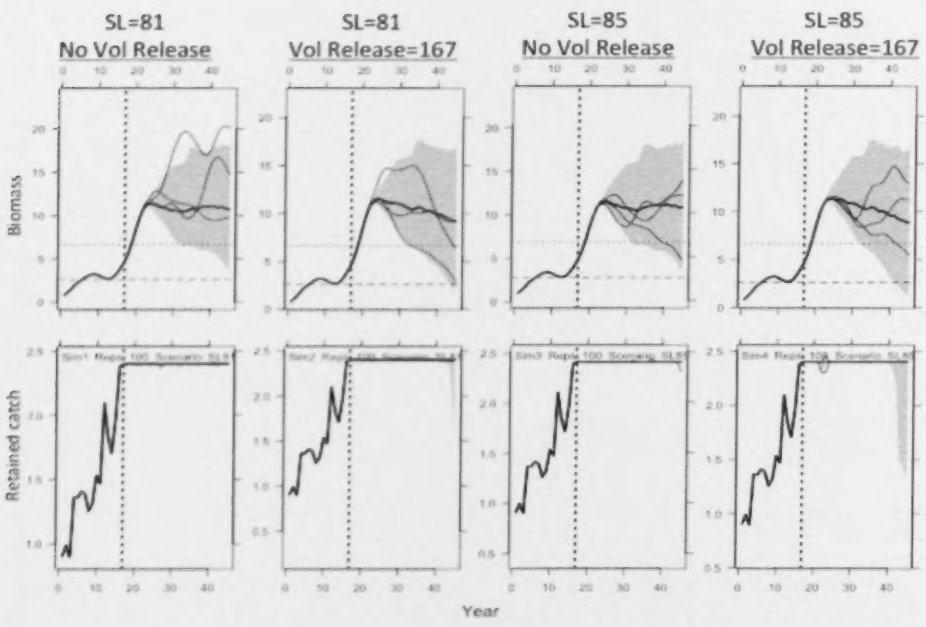

Figure A3.1. Simulated spawning stock biomass (top panels) and landed catch (bottom panels) for four harvest strategies based on constant 2,400 mt TAC combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut >167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

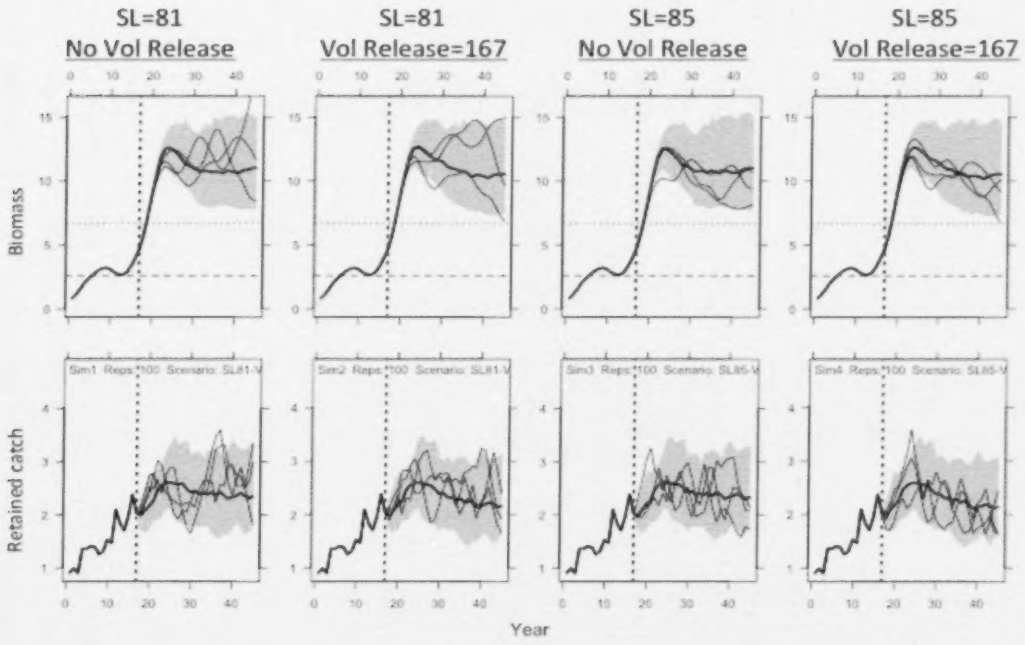

Figure A3.2. Simulated spawning stock biomass (top panels) and landed catch (bottom panels) for four harvest strategies based on constant F = 0.10 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

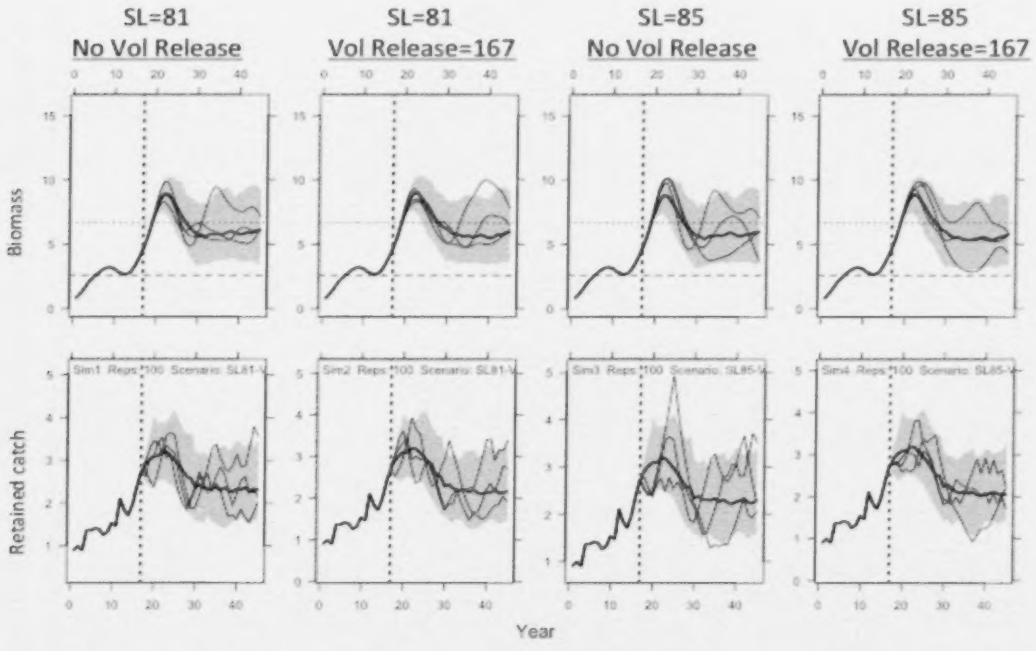

Figure A3.3. Simulated spawning stock biomass (top panels) and landed catch (bottom panels) for four harvest strategies based on constant F = 0.15 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

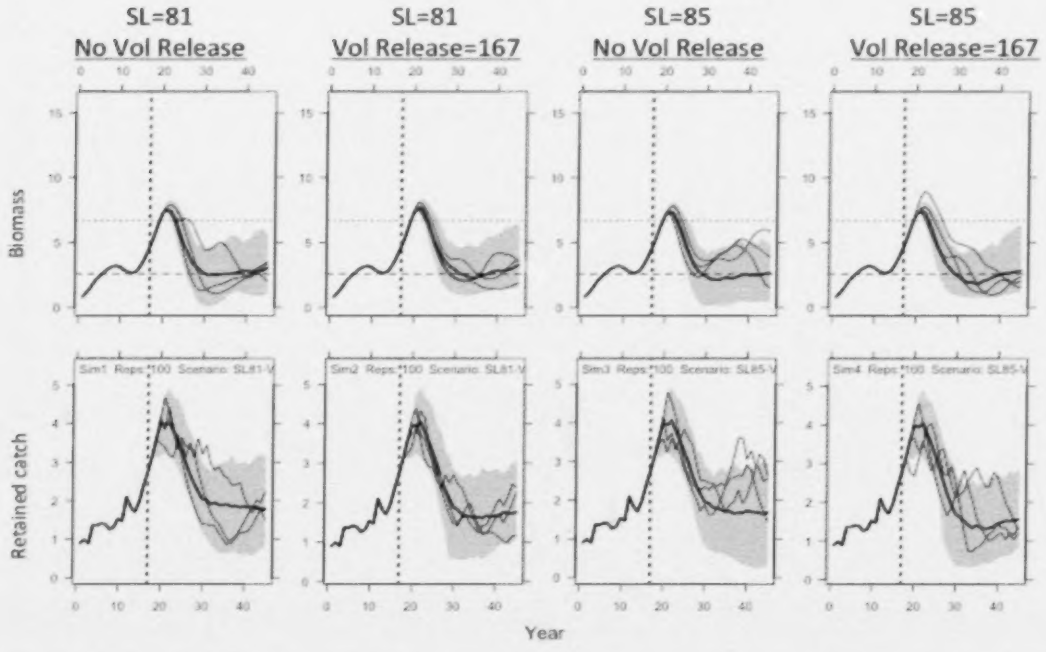

Figure A3.4. Simulated spawning stock biomass (top panels) and landed catch (bottom panels) for four harvest strategies based on constant F = 0.20 combined with the status quo size limit (SL=81 cm) and proposed higher size limit (SL=85 cm). Each size limit is also presented with and without voluntary release of large halibut > 167 cm. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). Median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates.

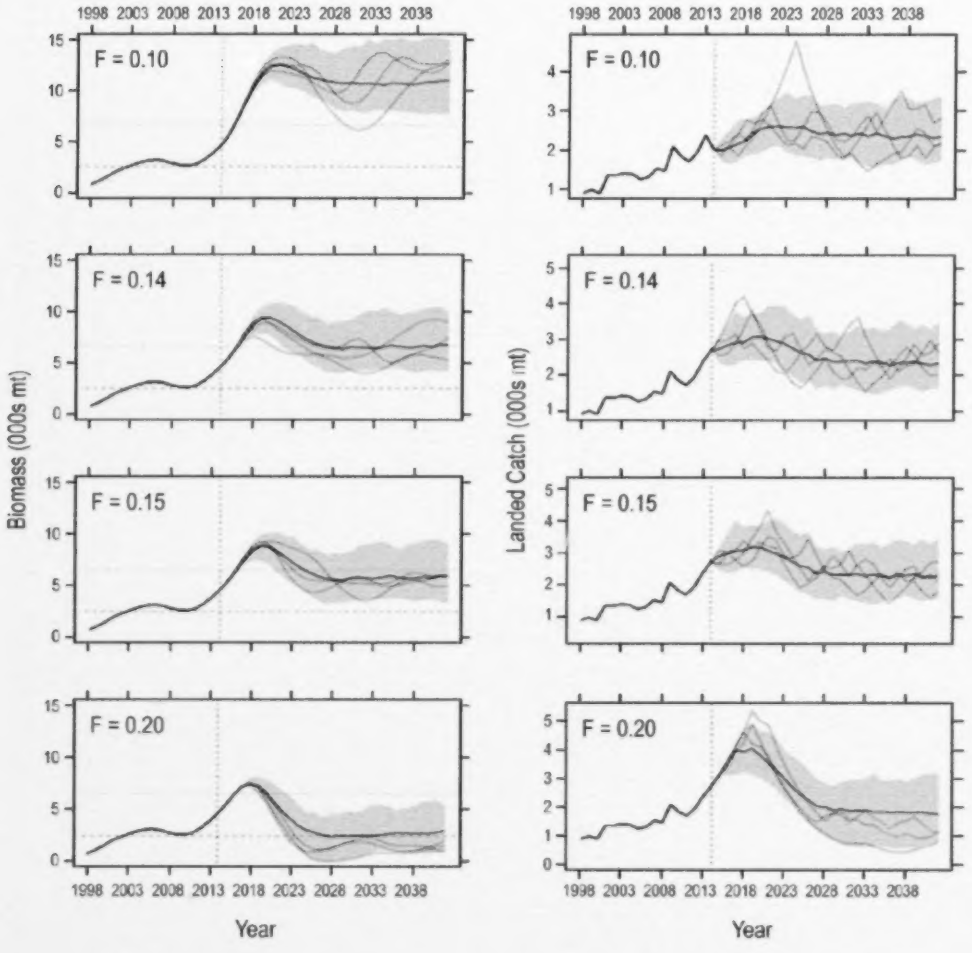

Figure A3.6. Simulated spawning stock biomass (left panels) and landed catch (right panels) for four harvest strategies based on constant fishing mortality rates F=0.10, 0.14, 0.15, and 0.20 and TAC changes of less than 15%. Horizontal lines in the biomass plots indicate the limit (lower dashed line) and upper stock (upper dotted line) biological reference points and the gray polygons delimit the central 80% of biomass levels from 100 simulation replicates (the lower limit of the shaded region is the lower 10th percentile of the simulated biomass levels). The median outcomes are indicated by the thick black lines and the thin lines (3 per plot) are from three individual simulation replicates. Note the y-axis for the landed catch varies.